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ENGINEERING DESIGN HANDBOOK

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HYDRAULIC FLUIDS

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HEADQUARTERS, U.S. ARMY MATERIEL COMMAND

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ENGINEERING DESIGN HANDBOOK
HYDRAULIC FLUIDS

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PREFACE

The Engineering Design Handbook Series of the Army Materiel Command is a coordinated series of handbooks containing basic information and fundamental data. The handbooks are authoritative reference books of practical information and quantitative facts helpful in the design and development of materiel that will meet the tactical and technical needs of the Armed Forces.

The use of hydraulics for power transmission and control has increased spectacularly in the past few decades. There are numerous reasons for this trend. The forces available in electrical systems are limited. Mechanical systems frequently require complex, and sometimes impractical, linkages for remote use of power. In applications requiring transmission of large amounts of power or large forces, the power-to-weight ratio of electrical or mechanical systems is generally much lower than that of hydraulic systems. The general field of hydraulic power transmission has been developing in both the equipment and fluid areas. Virtually every major piece of stationary and mobile equipment used by industry and the Armed Forces now incorporates at least one hydraulic system.

The objectives of this Handbook are: (1) to collect diverse sources of information to conserve time, materials, and money in the successful design of new equipment, (2) to provide guidance in capsule form for new personnel, Armed Forces contractors, or experienced design engineers in other fields who require information about hydraulic fluids, (3) to supply current fundamental information, and (4) to place the reader in a position to use new information generated subsequent to the publication of this handbook. To meet these objectives, the handbook has been written to provide the necessary background regarding hydraulic equipment and fluids so that more complete information and data available in the references can be utilized.

This handbook is organized into six chapters. Chapter 1 presents the inherent advantages, disadvantages, and areas of application of electrical, mechanical, and hydraulic systems along with a brief review of the principles of hydraulics. Chapter 2 includes descriptions of the major types of hydraulic circuit components and explanations, where applicable, of the methods of operation. Chapter 3 discusses the important properties of hydraulic fluids. These discussions are directed toward the significance of each property and the method(s) and accuracy of determination. Chapter 4 presents fluids currently conforming to Federal Specifications along with pertinent information from each specification. This chapter also includes a review of new nonspecification fluids which may find applications under extreme environmental conditions. Chapter 5 discusses additives frequently required to modify properties of base stock fluids. Chapter 6 presents the methods of handling and storing hydraulic fluids.

The text of this handbook was prepared by D. R. Wilson, M. E. Campbell, L. W. Breed, H. S. Hass, and J. Galate of Midwest Research Institute under subcontract to the Engineering Handbook Office of Duke University, prime contractor to the U.S. Army Materiel Command for the Engineering Design Handbook Series. Many helpful

comments were supplied by J. Messina of Frankford Arsenal and other members of the Ad Hoc Working Group of which Mr. Messina was chairman.

The Handbooks are readily available to all elements of AMC including personnel and contractors having a need and/or requirement. The Army Materiel Command policy is to release these Engineering Design Handbooks to other DOD activities and their contractors and other Government agencies in accordance with current Army Regulation 70-31, dated 9 September 1966. Procedures for acquiring these Handbooks follow:

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All requests—other than those originating within the DOD—must be accompanied by a valid justification.

Comments and suggestions on this handbook are welcome and should be addressed to:

U.S. Army Research Office-Durham
Box CM, Duke Station
Durham, North Carolina 27706

CHAPTER 1

INTRODUCTION

1-1 GENERAL

The development of our present level of technology has depended on the evolution of methods for the generation, distribution, and utilization of power. The energy requirements of the domestic population and the national defense effort increase at a rate of 2 to 3 percent per year. Various estimates place the rate of energy consumption in the United States at 1.0 to 1.5×10^{17} Btu per year by the year 2000 (Ref. 1). This increasing demand for power requires the continued development of methods for power transmission, control, and utilization. Fluid power technology plays an important role in this task and promises to be even more important in the future.

1-2 METHODS OF TRANSMITTING POWER

The majority of contemporary power transmission systems can be classified as electrical, mechanical, or fluid. Fluid power systems can be further divided into pneumatic and hydraulic systems, depending on the fluid medium used to transmit force. The fluids employed in pneumatic power and control systems are gases which are characterized by high compressibility. In contrast, hydraulic fluids are relatively incompressible liquids.

1-2.1 ELECTRICAL POWER TRANSMISSION

Power is transmitted electrically by imposing an electromagnetic field on a conductor. Electric systems are especially suitable for power transmission over long distances and are best applicable to low-power operations.

Magnetic saturation, a fundamental limitation of electrical machines, limits the torque developed by an electric motor. Material limitations also affect the

speed with which electrical servomechanisms can respond. Heat dissipation is a problem of frequent importance in electrical power transmission.

1-2.2 MECHANICAL POWER TRANSMISSION

Mechanical power transmission systems employ a variety of kinematic mechanisms such as belts, chains, pulleys, sprockets, gear trains, bar linkages, and cams. They are suitable for the transmission of motion and force over relatively short distances. The disadvantages of mechanical systems include lubrication problems, limited speed and torque control capabilities, uneven force distribution, and relatively large space requirements.

1-2.3 PNEUMATIC POWER TRANSMISSION

Pneumatic power is transmitted by the pressure and flow of compressed gases. The most common gas used is air. Pneumatic systems use simple equipment, have small transmission lines, and do not present a fire hazard. Disadvantages include a high fluid compressibility and a small power-to-size ratio of components. Pneumatic power systems are more elastic than mechanical systems and are very sensitive to small changes in pressure or flow. For this reason they are especially suited for pilot or control systems.

1-2.4 HYDRAULIC POWER TRANSMISSION

Hydraulic power is transmitted by the pressure and flow of liquids. For many years petroleum oils were the most common liquids, but other types of liquids are now finding widespread use. Hydraulic systems are mechanically stiff, and can be designed to give fast operation and move very large loads. They can be employed over greater distances than mechanical types but not as far as electrical systems.

Fitch (Ref. 2) lists the following advantages of hydraulic power systems:

- (1) Large torques and forces transmitted to any part of a machine
- (2) Cushioning for shock loads
- (3) Reversible, infinitely variable speed and load control
- (4) Completely automatic operations
- (5) Accurate position control for linear and rotary elements
- (6) Power linkage where kinematic linkage is impractical
- (7) Reduction of wear by the self-lubrication action of the transmission medium
- (8) Safe power system operation for both operator and machine.

Some of the major disadvantages of hydraulic systems are:

- (1) Impairment of system operation by contamination
- (2) Hydraulic fluid leakage
- (3) Fire hazards with flammable hydraulic fluids.

The functions of a hydraulic fluid are to transmit force applied at one point in the system to some other location and to produce any desired change in direction or magnitude of this force. To carry out this function in the most efficient manner, the hydraulic fluid must be relatively incompressible and must flow readily. In addition, the hydraulic fluid must perform certain other functions—such as lubrication and cooling—which are secondary in nature, but are important to the overall operation of the hydraulic system.

1-3 PRINCIPLES OF HYDRAULICS

1-3.1 GENERATION AND USE OF FLUID POWER

The use of hydraulic fluids to generate and transmit power is based upon physical laws which govern the mechanics of liquids. The principles of fluid mechanics, including both hydrostatics and fluid dynamics, have been developed over a period of several centuries and now constitute a fundamental branch of science and engineering. A knowledge of the application of these principles to the design and use of fluid power systems can be obtained by a study of any of several references drawn from the vast literature of fluid mechanics (Refs. 2, 3, 4, 5).

1-3.1.1 Fluid Power Circuits

The application of fluid power requires some type of fluid circuit. Many different circuit designs are possible for a given application. However, most hydraulic circuits represent some variation of a few basic circuit designs such as pump circuits, fluid motor circuits, accumulator or intensifier circuits, and control circuits.

All hydraulic circuits consist of some combination of six basic components: (1) a source of pressure, e.g., a pump; (2) a means of converting pressure into mechanical motion, e.g., a hydraulic motor or actuator; (3) fluid-transfer piping; (4) pressure, directional, and flow controls; (5) a fluid reservoir; and (6) a hydraulic fluid. The output of the hydraulic circuit is determined by the manner in which the various components are arranged. The individual components are described in Chapter 2.

1-3.1.2 Symbolic Representation of Components

The rapid development of fluid-power applications following World War II created a need for standard fluid power symbols and specifications to facilitate communication and provide a widely accepted means of representing fluid-power systems. This need was first met by the Joint Industry Conference (JIC) which published a set of graphical symbols for system components in September 1948. In 1958, the American Standards Association (ASA) adopted symbols based upon a revision of the JIC symbols. Since then, the ASA standards have been periodically revised. The current standard is USA Standard Y32.10-1967, *Graphic Symbols for Fluid Power Diagrams* (Ref. 6).

Graphic fluid power symbols are now widely used both for preparing circuit diagrams and as an aid in circuit design and analysis. They illustrate flow paths, connections, and component functions but do not indicate operating parameters or construction details. There are nine basic symbol classifications—fluid conductors, energy and fluid storage, fluid conditioners, linear devices, controls, rotary devices, instruments and accessories, valves, and composite symbols. A detailed discussion of the use and meaning of the ASA fluid power symbols can be found in the ASA Standard (Ref. 6); however, a brief explanation of a few of the more common symbols will aid the reader in further study.

(1) *Valves*: The basic valve symbol consists of one or more squares called envelopes, the number of envelopes corresponding to the number of valve positions. Inside each envelope are lines representing the flow

path and flow conditions between ports. The connection lines are drawn to the envelope representing the neutral position. The flow paths of the actuated valve are visualized by mentally shifting the corresponding envelope to the port position. Consider, for example, the three-position valve illustrated in Fig. 1-1. The normal position of the four-port valve is that of blocked flow, represented by the center envelope. To obtain the flow condition represented by the left envelope, that envelope is mentally shifted to the center position. Conversely, the crossed-flow path of the right envelope is obtained by mentally shifting the right envelope to the center position. Multiposition, multiport valves of any complexity can be represented by a suitable combination of such symbols.

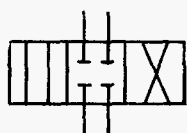


Fig. 1-1. Graphic Symbol for a Three-position, Four-port Hydraulic Valve

(2) *Rotary pumps and motors:* The basic symbol for a hydraulic pump is a circle with connecting lines indicating ports, and triangles indicating flow direction (Fig. 1-2(A)). Variable displacement is indicated by an arrow through the envelope at an angle. Pressure compensation is denoted by a short vertical arrow. Motors are distinguished from pumps by the location of the flow direction triangles. Flow triangles point outwards for pumps and inwards for motors (Fig. 1-2(B)). The envelope for an oscillatory device is a closed semicircle (Fig. 1-3).



Fig. 1-2. Graphic Symbols for (A) a Hydraulic Pump With Variable Displacement and Pressure Compensation; and (B) a Hydraulic Motor With Variable Displacement



Fig. 1-3. Graphic Symbol for a Hydraulic Oscillatory Device

(3) *Volume controls:* Orifice-type volume flow controls, such as globe and needle valves, are indicated graphically by arcs on both sides of the flow line (Fig. 1-4). If the size of the restriction is variable, an arrow is placed at an angle through the symbol. Pressure compensation is indicated by adding a rectangular envelope and a small vertical arrow across the flow line.

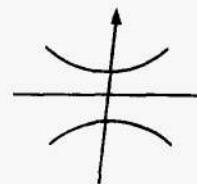


Fig. 1-4. Graphic Symbol for a Variable-flow Hydraulic Volume Control, Such as a Needle Valve

(4) *Pressure controls:* Pressure relief valve symbols consist of a square envelope with a closed normal position and an actuated position which relieves to a reservoir. Upstream pilot pressure is shown by a broken line (Fig. 1-5). Pressure reducing valves have an open neutral position and a downstream pilot pressure.

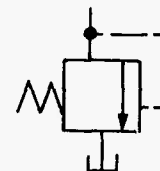


Fig. 1-5. Graphic Symbol for a Pressure Relief Valve

1-3.1.3 Uses of Hydraulic Power

The manner in which hydraulic power can be put to use is limited primarily by the imagination of the designer. Hydraulic power has found its most extensive use in manufacturing and construction machinery. Fluid-power operated presses and material-handling machinery are common fixtures in any production plant. In construction and earth-moving industries, hydraulic power is used on almost every piece of equipment. Other industries making extensive use of fluid power are aerospace, agriculture, petroleum, automotive, chemical, and food processing.

1-3.2 REQUIREMENTS FOR HYDRAULIC FLUIDS

The hydraulic fluid is an essential and important component of any hydraulic power or control system. No other component of the circuit must perform as many functions or meet as many requirements as the hydraulic fluid. The hydraulic fluid must not only provide a medium for efficient power transmission, but it must also lubricate, cool, protect from corrosion, not leak excessively, and perform numerous other functions depending on the system design. However, even if a hydraulic fluid can adequately perform these system functions, it may still be less than satisfactory in terms of usage and compatibility factors. In many hydraulic systems, it is necessary that the hydraulic fluid be nontoxic and fire-resistant. It must be compatible with the structural materials of the system. The hydraulic fluid should exhibit stable physical properties during a suitable period of use. It should be easy to handle when in use and in storage, and it is desirable, of course, that it be readily available and inexpensive.

The selection of a hydraulic fluid is further complicated by the vast number of liquids currently available. These range from water and mineral oils to special-purpose synthetic liquids. It is thus necessary for the system designer to have at least an elementary understanding of the terminology prevalent in the specification of hydraulic fluids.

1-3.2.1 System Dependency of the Hydraulic Fluid

1-3.2.1.1 Temperature

Temperature is a system parameter rather than a characteristic of the fluid. However, the physical properties of hydraulic fluids are influenced by the operating temperature. High temperature can cause a decrease in viscosity and lubricity, resulting in increased leakage through seals and detrimental friction and wear. Many hydraulic fluids experience molecular breakdown at elevated temperatures.

Viscosity increases with decreasing temperature, and thus the lowest operating temperature for a given liquid is that corresponding to the maximum viscosity which can be satisfactorily accommodated by the system.

Hence, an important requisite in the selection of hydraulic fluids is a thorough knowledge of the storage temperature, the average operating temperature, the high and low operating temperatures, and the tempera-

tures of local system hot spots. With these known, it then becomes necessary to know the manner in which the liquid properties vary within the system temperature range.

1-3.2.1.2 Viscosity

Viscosity, often referred to as the most important single property of a hydraulic fluid, is the property which characterizes the flow resistance of liquid. Low-viscosity liquids transmit power more effectively, whereas high viscosity is required to lubricate and to reduce leakage. Thus, the allowable viscosity range depends on a compromise between the power-transmission characteristics on the one hand and the sealing and lubricating properties on the other.

Viscosity depends upon temperature and pressure, and generally increases with decreasing temperature or increasing pressure. The viscosity index (V.I.) is a measure of the temperature dependence. Liquids with a high viscosity index exhibit a smaller variation of viscosity with temperature than do liquids with a low V.I. Low-viscosity liquids are less affected by pressure than high-viscosity liquids. Liquids which exhibit a large variation of viscosity with temperature usually exhibit a large viscosity change with pressure.

Another factor which can influence the viscosity is the rate of shear. Liquids with large polymer molecules can exhibit a temporary decrease in viscosity when subjected to high shear rates. If the liquid is subjected to shear-rate conditions which tend to break down large molecules, permanent changes in viscosity can result.

Viscosity affects many operational factors in a hydraulic system—mechanical friction, fluid friction, pump slippage, cavitation, leakage, power consumption, and system control ability. The use of a hydraulic fluid with a low viscosity can lead to increased pump slippage, excessive wear of moving parts, and hydraulic fluid loss due to leakage. A viscosity which is too high will cause increased pressure loss and power consumption and, as a result of liquid friction, can lead to excessive system temperatures.

1-3.2.1.3 Compatibility With System Materials

Chemical compatibility of a hydraulic fluid with the system materials sometimes requires compromises in the selection of the hydraulic fluid or the materials of construction. The hydraulic fluid should be chemically inert and should not react with materials of the system

or the environment. In turn, the construction materials should not affect the properties of the hydraulic fluid.

Corrosion prevention is one of the many functions of the hydraulic fluid. Air and moisture are always present, to some degree, in hydraulic systems. Therefore, most hydraulic fluids have a rust inhibitor and/or a metal deactivator which coats the metal surfaces.

Copper is an undesirable material for hydraulic systems because it serves as a catalyst for the oxidation of many hydraulic fluids. Liquid oxidation rate increases with increasing temperature and is enhanced by the presence of water, air, and solid contaminants in the fluid. Chemical additives are commonly used in hydraulic fluids to control the rate of oxidation.

Seal materials often present a difficult design problem from the viewpoint of compatibility with hydraulic fluids. Natural rubber reacts in some manner with nearly all hydraulic oils. The reaction of synthetic rubbers depends upon the type of synthetic and the liquid to which it is exposed. The aniline point can be used as a relative indication of the effect of mineral oils on rubber. Oils with high aniline points generally cause less swelling or shrinking than oils with low aniline points. High aromaticity of a mineral oil is usually an indication that the oil will cause a high degree of swelling in conventional rubber.

As mentioned above, compatibility is not solely a problem of selecting a hydraulic fluid. When a hydraulic fluid is found that has desirable performance characteristics but is chemically incompatible with some system material, a better overall system is often obtained if the construction material is changed rather than the hydraulic fluid. However, in many military applications, a change in construction material is not easily accomplished. It has often been necessary to change the hydraulic fluid or develop a new hydraulic fluid for existing equipment.

1-3.2.1.4 Hydraulic System Accuracy, Speed of Response, and Stability

The type of hydraulic fluid used in a hydraulic system is an important factor in determining system accuracy, response speed, and stability. These characteristics of a system are not determined by any one property of a liquid but depend on the combination of several properties, especially viscosity (par. 1-3.2.1.2) and compressibility (par. 1-3.2.1.7). If the hydraulic fluid is one of the more compressible types, much of the energy supplied to the system is used in deforming the liquid with a resultant loss in response speed and accuracy of system component operation. Also, if liquid

transmission lines are long, compression delays in control signals can result in interference of various signals and erratic component response. If a hydraulic fluid having too high a viscosity is used, flow resistance and pressure drops in the system increase and operation becomes sluggish. If the viscosity is too low, control precision may be lost.

1-3.2.1.5 Fluid Stability (Temperature and Shear)

The stability of a hydraulic fluid determines the length of time during which it remains useful either in service or in storage. A stable liquid exhibits only small changes in characteristics over a suitable period. The degree to which a hydraulic fluid is stable depends upon two factors: (1) its tendency to react with the environment, and (2) the changes induced by operational use.

The oxidation stability of a hydraulic fluid is measured by its tendency to decompose or polymerize. Oxidation reactions are markedly accelerated by an increase in temperature. Over a prolonged period, accumulation of oxidation products can cause deterioration of the hydraulic fluid appearing as increased viscosity and sludge deposits. Since all liquids oxidize to some extent at all temperatures, a hydraulic fluid is considered to possess oxidation stability if the changes induced by oxidation over a reasonable period of time do not render the hydraulic fluid unsatisfactory for operational use.

Changes in viscosity can also result from (1) thermal decomposition at local hot spots, and (2) the breakdown of molecules due to high rates of shear.

Like the other factors discussed, stability requirements depend upon system design as well as hydraulic fluid selection. For example, oxidation and hydrolytic stability of a given hydraulic fluid can be extended if the hydraulic system is designed to minimize the amount of air and water which can enter the fluid circuit. Stability is discussed in further detail in Chapter 3.

1-3.2.1.6 Lubricity

The hydraulic fluid must serve as a lubricant between moving parts of the system in order to minimize friction and wear. To do so, it must have a suitable viscosity and must possess adequate lubricity. The term "lubricity" refers to the ability of a liquid to reduce friction and prevent wear under even the most severe circumstances. Lubricity is a complex function that

refers to the shear strength of a thin lubricating film. A liquid that forms a film of low shear strength is said to have good lubricity.

The ability of a liquid to form a film on a surface is important in lubrication. The film should be capable of supporting the loads encountered during operation. Breakdown of the lubricating film causes wear and shortens the life of the system components. In general, higher viscosity liquids are better able to maintain films than those of lower viscosity. However, system considerations other than lubrication limit the value of viscosity in some applications. Antiwear additives provide a solution to some of these problems.

1-3.2.1.7 Pressure

The reduction of volume of a liquid under pressure is a measure of the compressibility of the liquid. Compressibility influences the power required by the pump, the time required to generate pressure, the speed with which the transmission and control systems respond to input, and the manner in which energy is converted by pressure reduction. The bulk modulus is the reciprocal of the compressibility and is always a positive quantity. A high bulk modulus indicates low liquid elasticity and, hence, a small spring effect when subjected to a pressure change. A liquid with high bulk modulus is desirable in order to obtain good dynamic performance in a hydraulic system. Entrained air in the fluid reduces the bulk modulus. Pressure and temperature also affect the bulk modulus. For most liquids, the bulk modulus decreases with increasing temperature and also with decreasing pressure.

1-3.2.1.8 Lacquer and Insoluble Material Formation

The hydraulic fluid should remain homogeneous while in use. The formation and deposit of insoluble materials on parts of the system can cause system malfunction or failure. Insoluble materials can be formed by many different processes. Oxidation, contamination, thermal degradation, hydrolytic degradation, etc., can all produce insoluble materials. Changes in the hydraulic fluid caused by the above processes can also affect the solubility of additives and result in the additives becoming insoluble. Insoluble materials can plug small orifices, reduce clearances, damage surfaces, or form deposits on working surfaces. The deposits show up as coatings, varnishes, lacquers, etc.

1-3.2.2 Other Considerations

1-3.2.2.1 Availability

It is obviously desirable that a hydraulic fluid be readily available. If a hydraulic fluid possesses widely applicable properties and is competitive in terms of cost, it will usually be readily available.

1-3.2.2.2 Cost

Several factors must be considered in the evaluation of the cost of a hydraulic fluid. The original cost, the service longevity, storage costs, and rate of system leakage enter into the overall cost evaluation. The purchase of an expensive hydraulic fluid is justified if its properties can result in lower ultimate system costs because of reduced replacement frequency, increased component life, or other factors. However, consideration should be given to the economy afforded by changes in system design to allow use of a less expensive hydraulic fluid.

1-3.2.2.3 Handling

The ease with which a hydraulic fluid can be handled is important to the user and to maintenance personnel. Toxicity is perhaps the first factor to consider in evaluating handling characteristics. The hydraulic fluid, its vapor, and its decomposition products should have very low toxicity, in terms of inhalation, ingestion, or contact with the skin. Toxic liquids can be used only if extreme precautions are taken to insure no harmful effects to the operating and maintenance personnel.

A hydraulic fluid should not have an unpleasant or nauseating odor. Although odor does not influence performance, it is important to the user.

1-3.2.2.4 Storage

The storage characteristics of a hydraulic fluid are closely related to chemical stability and handling characteristics. The properties of a hydraulic fluid should not deteriorate if the fluid stands in storage for long periods. Precautions should be taken to insure that contaminants cannot enter the stored hydraulic fluid. Oxidation stability is often used as a criterion in evaluating the storage characteristics.

1-3.2.2.5 Contamination

A hydraulic fluid is subjected to several sources of contamination, both in use or in storage. Air and moisture can leak into the system. These contaminants promote oxidation and hydrolysis. Entrained water can also cause emulsions which, in turn, tend to collect solid impurities. It should be noted that emulsions are formed more readily in contaminated liquids than in clean ones. Solid contaminants can result from fabrication, handling, or cleaning procedures, and from wear debris. Solid contaminant particles can increase wear, accelerate corrosion, and contribute to sludge and foam formation. Oxidation products and the compounds formed by additive decomposition are contaminants.

Several methods are used to remove various contaminants. Filtration devices, which are discussed in Chapter 2, can be used to remove solid particles. Magnetic plugs and filters can remove ferrous metal particles. Storage in settling tanks allow solid particles to settle out by gravitational forces. Centrifuges are sometimes used to remove heavy contaminants. If the liquid has good demulsibility properties, water can be

removed after it separates from the liquid in a reservoir or storage vessel.

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CHAPTER 2

POWER TRANSMISSION EQUIPMENT

2-0 LIST OF SYMBOLS

A = cross-sectional area or area of a radiating surface, ft^2
 D = diameter, in.
 D_e = equivalent diameter, in.
 F = force, lb; or in heat transfer, a dimensionless factor which accounts for the geometric orientation of surfaces and their emittances
 f = coefficient of friction, or friction factor
 G = flow rate, gpm
 h = convective film coefficient, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})$
 K = friction loss coefficient
 k = thermal conductivity, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
 L = damping length or length of a pipeline, ft
 L_e = equivalent length of a pipeline, ft
 ℓ = thickness of a material, ft
 N = number of pound moles
 P = pressure, psi or mm Hg
 P_f = liquid pressure, psi
 P_g = gas pressure, psi
 P'_g = final accumulator pressure after a pressure or volume change, psi
 Q = volumetric flow rate, gpm; or rate of heat flow, Btu/hr
 Q_p = increase in thermal energy due to pumping, Btu/hr
 Q_f = increase in thermal energy due to friction in a valve, Btu/hr
 R = universal gas constant, $10.72 \text{ psia-ft}^3/^\circ\text{R-lb mole}$
 $^\circ\text{R}$ = degrees Rankine ($^\circ\text{F} + 460$)
 R_n = thermal resistance of system component n , $\text{hr-}^\circ\text{F/Btu}$

s = specific gravity of liquid
 T_a = ambient temperature
 T'_a = final ambient temperature after a pressure or volume change
 U = liquid velocity, fps; or overall heat transfer coefficient, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})$
 V = volume, ft^3 , in^3 , or cm^3
 V'_g = final gas volume
 Z_g = compressibility factor of gas, dimensionless
 Z'_g = final compressibility factor of gas, dimensionless
 ΔP = change in pressure, psi
 ΔT = temperature difference, $^\circ\text{F}$
 ΔT_{total} = total temperature difference across which heat is being transferred, $^\circ\text{F}$
 η = decimal operating efficiency
 σ = Stefan-Boltzmann constant, $0.1714 \times 10^{-8} \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{R}^4)$

Note: Where more than one set of units have been specified, or no units specified, a consistent set of units must be used.

2-1 GENERAL

The preceding chapter pointed out that the hydraulic fluid performs a basic function in a hydraulic power or control system and must satisfy numerous requirements to perform adequately in a given circuit. Furthermore, the hydraulic fluid influences the operation of the system components and they, in turn, affect the performance of the hydraulic fluid. Hence, the components of a system cannot be designed or specified independently of the hydraulic fluid, nor can the hydraulic fluid be selected independently of the component design. The hydraulic circuit, involving both mechanical

components and hydraulic fluid, must be designed as an integral system.

This chapter is devoted to a discussion of the mechanical components of the system and their interrelationship with the hydraulic fluid. No attempt is made to provide a comprehensive discussion of equipment design. For this, the reader is referred to any one of several works devoted to the subject (Refs. 1, 2, 3, 4, 5).

To illustrate the manner in which system components are integrated into a hydraulic circuit, consider the circuit illustrated in Fig. 2-1. This is a rotary liquid motor circuit which produces constant torque. To do so, a constant hydraulic pressure must be maintained on the motor. This condition is achieved by using a pressure regulator valve upstream of the motor. Constant pressure could also be obtained by using a pressure-compensated, variable-displacement pump.

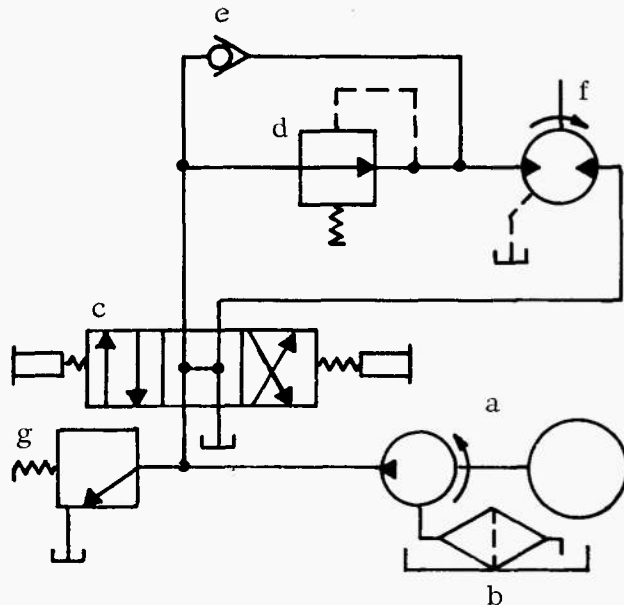


Fig. 2-1. Rotary Motor Circuit Which Produces Constant Torque [Shown are: (a) hydraulic pump and drive motor, (b) reservoir and strainer, (c) manually operated control valve, (d) pressure regulator valve, (e) check valve, (f) hydraulic motor, and (g) pressure relief valve]

The circuit of Fig. 2-1 contains all six of the basic components mentioned in Chapter 1. The pump (a), driven by an electric motor, serves as the source of fluid energy. The fixed-displacement hydraulic motor (f) converts hydraulic energy into mechanical energy. Hydraulic piping is provided between the system components. Directional controls are provided by the manually actuated control valve (c) and the check valve (e).

The pressure regulator (d) and the relief valve (g) provide pressure control. A fluid reservoir (b) serves both for storage and as a system vent location. Less obvious is the hydraulic fluid without which the system could not perform a single useful function.

The design of a hydraulic system encompasses many factors. Given a particular power transmission or control problem, the designer must first determine what type of components will accomplish the desired objective. A conceptual layout of the system is then followed by engineering analysis to determine the necessary size, configuration, and details of the hardware. Suitable materials must be selected for component construction, and engineering drawings must be prepared. Underlying each of these steps is the nebulous factor commonly referred to as good engineering practice. This entails a knowledge, usually acquired through experience, of the features which constitute good design practice, i.e., those factors which cannot be readily subjected to precise mathematical and engineering analysis.

The equations with which the designer constructs a mathematical model of a hydraulic system are, in general, nonlinear differential equations, frequently of second or higher order. Such equations usually require numerical solutions and, hence, digital and analog computers have become valuable aids in the design of hydraulic systems. A thorough engineering analysis begins with the specification of certain parameters which the system must satisfy—such as force or load requirements, stability, speed of response, accuracy, and resolution. The mathematical model is then manipulated until the desired specifications are met on paper. The resulting information can be used in system specification and fabrication.

However, a detailed computer solution of the equations which describe the system does not always result in a design which performs as predicted by the analysis. It is frequently possible, using the appropriate approximations and sound engineering practice, to design a system based upon hand computations which will perform as well as, or better than, one based upon a detailed computer analysis. Usually, it is desirable to use a preliminary hand-calculated analysis to optimize a subsequent, more detailed computer analysis. Mathematical techniques in the form of computer programs are now available, which facilitate detailed analysis by relieving the designer of the necessity of developing routines for the solution of complex nonlinear equations.

Merritt (Ref. 4) distinguishes between two types of parameters involved in hydraulic system design. A

hard parameter is defined as a physical quantity which can be measured with good precision and which remains essentially constant. A soft parameter, on the other hand, is a quantity which is difficult to measure or compute and, for a given system, can be determined only within a range of values. The most important design features of a system should be based upon hard parameters, if possible. Merritt points out that an important part of sound engineering design practice is the ability to distinguish between hard and soft parameters.

2-2 PUMPS

A hydraulic pump is a device used to impart motion to a liquid and thereby convert mechanical energy to hydraulic energy. It provides the force required to transmit power. Pumps are rated in terms of flow and pressure. The flow rating (volumetric output) is the amount of liquid which can be delivered by the pump per unit time at a specified speed. A pump does not produce pressure. The pressure developed at the outlet depends on the resistance to flow in the circuit.

Pumps are classified according to configuration or operating characteristics. One obvious classification is that of rotary or reciprocating pumps. Rotary pumps utilize a rotating assembly to transfer the fluid from the inlet to the outlet and to impart motion. Rotary pumps can be further classified as gear, vane, or rotating piston pumps. Reciprocating pumps employ a plunger or piston to impart motion to the fluid.

Pumps can also be classified as positive- or non-positive-displacement devices. Positive-displacement pumps move a definite amount of fluid during each stroke or revolution. They are most frequently used in hydraulic systems. Nonpositive-displacement, or hydrodynamic, pumps provide continuous flow. They are primarily low-pressure devices with high volumetric output.

Positive-displacement pumps can be of either fixed or variable displacement. The output of a fixed-displacement pump is constant at a given pump speed. The output of a variable-displacement pump can be changed by adjusting the geometry of the displacement chamber.

2-2.1 GEAR PUMPS

Gear pumps are the most widely used pumps for hydraulic systems. They are available in a wide range of flow and pressure ratings. The drive and gears are the only moving parts.

2-2.1.1 External Gear Pumps

In external gear pumps, two or more gears mesh with minimum clearance. The gear motion generates a suction at the inlet, which causes fluid to be drawn into the pump housing. The liquid is drawn through the pump and is displaced as the teeth mesh on the outlet side.

(1) *Spur gear pumps*: A spur gear rotary hydraulic pump is illustrated in Fig. 2-2. The two gears rotate in opposite directions and transfer liquid from the inlet to the outlet through the volume between the teeth and the housing. The output depends on tooth width and depth, and is largest for a minimum number of teeth. Involute teeth with a pressure angle of 20-30 deg are common in spur gear pumps. However, progressive-contact and edge-contact gears are sometimes used to avoid the severe loads generated by liquid trapped between the contact points of the meshed involute teeth.

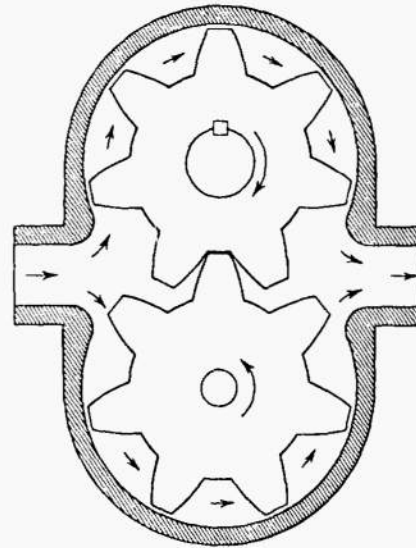


Fig. 2-2. Spur Gear Rotary Hydraulic Pump

[From: H. E. Merritt, *Hydraulic Control Systems*^{4*}. Used by permission of John Wiley and Sons]

The spur gear pump is a fixed-displacement pump. Output at a given speed decreases slightly with pressure. Typical operating characteristics are shown in Fig. 2-3. These curves are for a spur gear pump operating with a liquid of constant viscosity. This viscosity effect illustrates one of the ways in which the liquid influences the specification of system components.

⁴Superscript numbers refer to References at the end of each chapter.

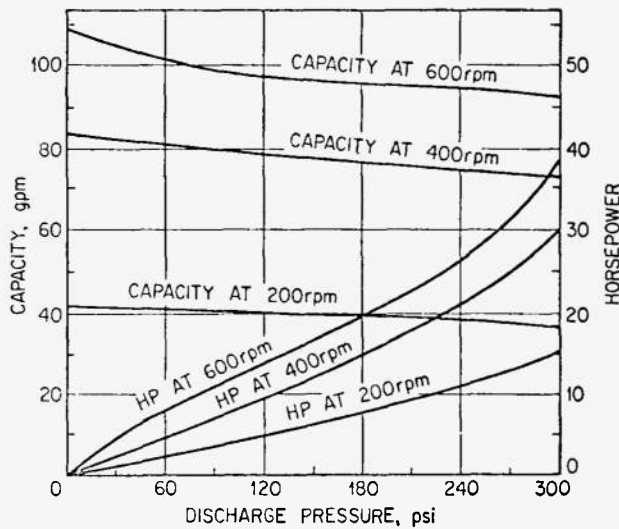


Fig. 2-3. Typical Operating Characteristic Curves for a Spur Gear Rotary Hydraulic Pump

[From: Pippenger and Hicks, *Industrial Hydraulics*.² Used by permission of McGraw-Hill, Inc.]

(2) *Helical gear pumps*: A variation of the external gear spur gear pump is the helical gear pump. The fact that several teeth are engaged simultaneously allows the helical gear pump to carry larger loads at high speeds than can the spur gear pump. Operation is similar to that of the spur gear pump, but with less noise and usually smaller flow pulsations. Because of the helical gear configuration, end thrusts are developed by helical gears. These forces act in opposite directions on the drive and driven gears.

(3) *Herringbone gear pumps*: Another variation of the external gear pump incorporates herringbone gears. Like all gear pumps, the herringbone device is a constant displacement pump. It is generally available for pressures up to about 2,000 psi but some models are rated at over 3,000 psi.

2-2.1.2 Internal Gear Pumps

There are two types of internal gear pumps: the crescent seal pump and the gerotor pump.

(1) *Crescent seal pumps*: The crescent seal pump consists of an inner and outer gear separated by a crescent-shaped seal (Fig. 2-4). The gears rotate the same direction, with the inner gear rotating at a higher speed. The liquid is drawn into the pump at the point where the gear teeth begin to separate and is carried to the outlet in the space between the crescent and the teeth

of both gears. The contact point of the gear teeth forms a seal, as does the small tip clearance at the crescent. This pump is generally used for low output applications at pressures below 1,000 psi.

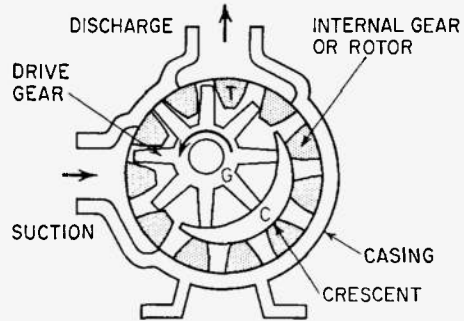


Fig. 2-4. Crescent Seal Internal Gear Hydraulic Pump [Shown are: crescent C, gear teeth T, and drive gear G]

[From: Pippenger and Hicks, *Industrial Hydraulics*.² Used by permission of McGraw-Hill, Inc.]

(2) *Gerotor pumps*: The gerotor pump consists of a pair of gears which are always in sliding contact (Fig. 2-5). The larger internal gear has one more tooth than the external gear. Both gears rotate in the same direction. Liquid is drawn into the chamber where the teeth are separating, and is ejected when the teeth again start to mesh. The seal is provided by the sliding contact. Gerotor pumps are restricted to low-pressure operation because of the loads generated by the hydraulic unbalance.

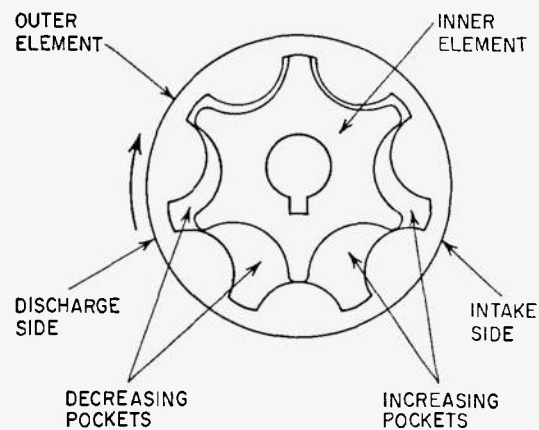


Fig. 2-5. Gerotor Internal Gear Hydraulic Pump

[From: Pippenger and Hicks, *Industrial Hydraulics*.² Used by permission of McGraw-Hill, Inc.]

2-2.2 VANE PUMPS

Vane pumps consist of a rotor mounted in a cam-shaped housing. The rotor is provided with radial slots which accommodate vanes. As the internal assembly rotates, the vanes are forced radially outward against the housing by centrifugal force sometimes assisted by springs. Vane pumps can operate at speeds up to 2,000 rpm and are available in pressure ratings to 2,500 psi. Their simple construction results in a high degree of reliability and easy maintenance. They are relatively low in cost and exhibit long operating life partially due to the fact that vane wear is accommodated by the radial motion of the vanes. They have comparatively high volumetric and overall efficiencies, and are available in a wide range of output ratings. Typical operating characteristic curves of a vane pump are shown in Fig. 2-6.

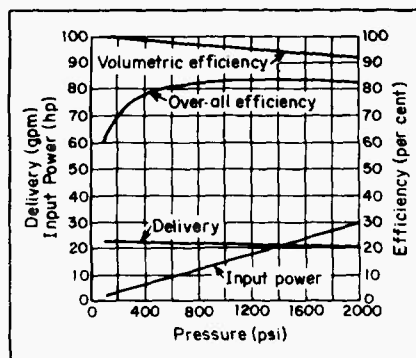


Fig. 2-6 . Typical Operating Characteristic Curves for a Vane Hydraulic Pump

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

Operating limitations of vane pumps are imposed by vane tip speed, bearing loads, and cavitation. The force exerted by the vanes against the housing can be controlled by using dual vanes, i.e., two vanes in each slot. Each of the dual vanes has a smaller contact area than a single vane. The dual vane design also provides a better seal between the vanes and the housing.

Vane pumps exhibit a good tolerance to liquid contamination. They are generally used with petroleum-base or Military Specification hydraulic fluids in mobile operations and with petroleum or fire-resistant hydraulic fluids in stationary applications. Discharge pulsations can sometimes constitute a problem if high response is desired.

2-2.2.1 Unbalanced Vane Pumps

In the unbalanced vane pump, the rotor and cam housing are eccentric (Fig. 2-7). The pump suction is generated in the region where the vanes begin to move outward. The liquid is carried around the rotor by the vanes, which form a seal with the housing and the end plates, and it is discharged as the vanes are forced back into the rotor slots by the eccentric housing.

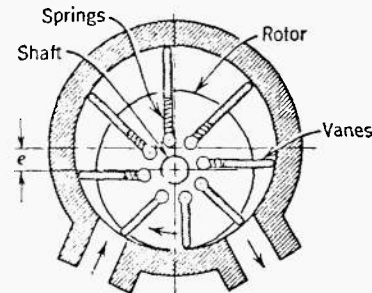


Fig. 2-7. Unbalanced Vane Hydraulic Pump

[From: H. E. Merrit, *Hydraulic Control Systems*.⁴ Used by permission of John Wiley and Sons]

Unbalanced vane pumps can be either fixed- or variable-displacement pumps. In the fixed-displacement pump the rotor-housing eccentricity is constant and, hence, the displacement volume is fixed. A constant volume of fluid is discharged during each revolution of the rotor. Variable displacement can be provided if the housing can be moved with respect to the rotor. This movement changes the eccentricity and, therefore, the displacement.

In addition to sliding vanes, rolling vanes and swinging vanes are also available in unbalanced vane pumps (Fig. 2-8). Each of these variations is hydrostatically unbalanced. This unbalance causes high bearing

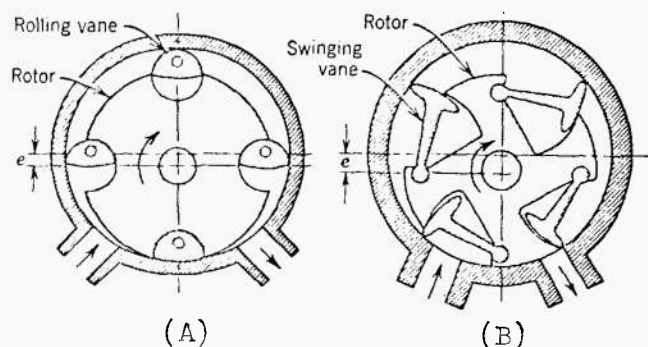


Fig. 2-8 . Vane-type Hydraulic Pumps and Motors (A) Rolling Vane, and (B) Swinging Vane

[From: H. E. Merrit, *Hydraulic Control Systems*.⁴ Used by permission of John Wiley and Sons]

loads and generally limits the application of unbalanced vane pumps to operating pressures less than about 1,500 psi (Ref. 4).

2-2.2.2 Balanced Vane Pumps

Hydraulic balance is achieved in the balanced vane pump in which the rotor is in an elliptic housing (Fig. 2-9). This configuration creates two diametrically-opposed displacement volumes. The two high-pressure zones balance the forces on the rotor shaft. In many such units no springs are provided to assist the outward motion of the vanes. This condition restricts operation to speeds above a minimum at which the centrifugal force is sufficient to hold the vanes against the housing. Other designs utilize springs for start-up and low-speed operation. Balanced vane pumps are necessarily fixed-displacement machines.

2-2.3 PISTON PUMPS

The applications for which the piston pump is well-suited are determined by its two principal advantages—high-pressure capability and high volumetric efficiency. In addition, the piston pump can operate at speeds over 2,000 rpm; is available in a wide range of output ratings; and provides a compact, lightweight unit for high power applications, low noise level when flow path is linear, and better system economy in the higher power ranges (above 20 hp).

Piston pumps are classified by the motion of the piston relative to the drive shaft. There are three categories—axial, radial, or rotating.

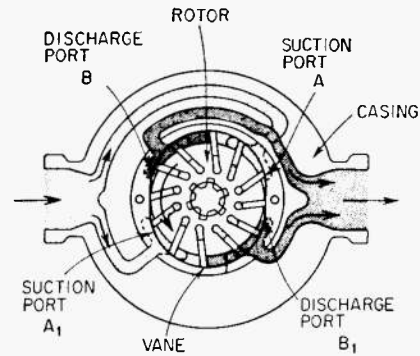


Fig. 2-9. Balanced Vane Hydraulic Pump

2-2.3.1 Axial-piston Pumps

In the axial-piston pump, rotary shaft motion is converted to axial reciprocating motion which drives the piston. Most axial-piston pumps are multi-piston designs and utilize check valves or port plates to direct liquid flow from inlet to discharge. Output can be controlled by manual, mechanical, or pressure-compensated controls. An axial-piston pump is shown in Fig. 2-10. Rotary drive motion is converted to reciprocating, axial piston motion by means of the thrust cam, or wobble plate, mounted on the drive shaft. Variable-displacement volume is provided by the internal valving arrangement. Axial-piston pumps are available with output ratings of over 100 gpm, and some types are rated at pressures above 5,000 psi.

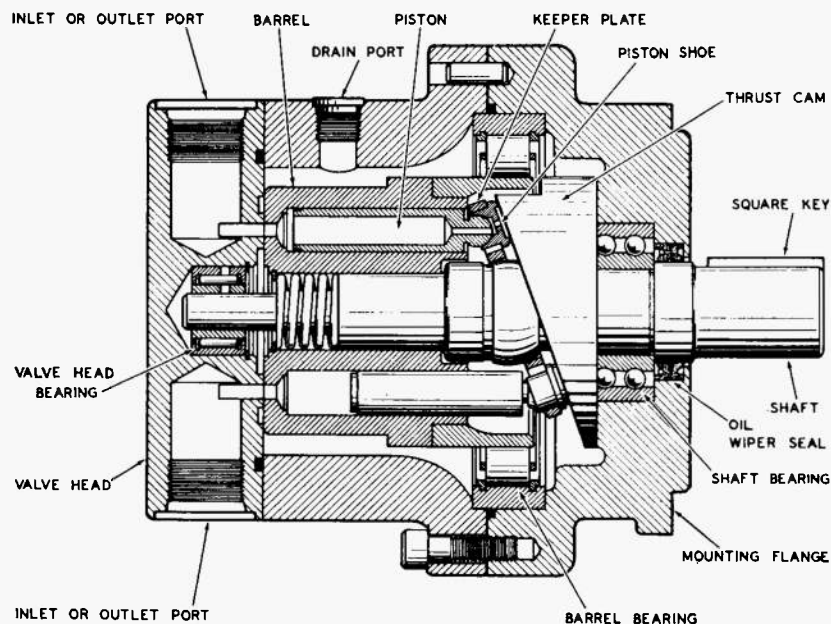


Fig. 2-10. Axial-piston Hydraulic Pump

[From: H. E. Merrit, *Hydraulic Control Systems*.⁴ Used by permission of John Wiley and Sons.]

2-2.3.2 Radial-piston Pumps

In a radial-piston pump, the pistons move perpendicularly to the shaft centerline. Two basic types of radial-piston pumps are available. One uses cylindrical-shaped pistons and the other uses spherical-shaped pistons. In the pump shown in Fig. 2-11, the pistons move in a rotating cylinder block and are forced outward by centrifugal force. In Fig. 2-11, only one piston is shown (in four positions); however, most pumps are multi-piston.

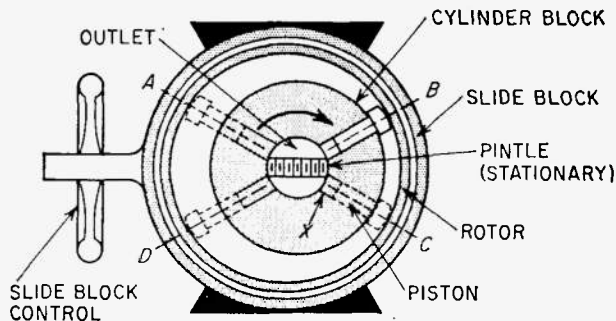


Fig. 2-11. Radial-piston Hydraulic Pump With Rotating Piston Housing [One piston is shown at four positions—A, B, C, and D]

[From: Pippenger and Hicks, *Industrial Hydraulics*². Used by permission of McGraw-Hill, Inc.]

A radial-piston pump which employs spherical pistons is shown in Fig. 2-12. The pistons move radially in a rotating cylinder block. They are forced against the eccentric housing by centrifugal force. Liquid porting is achieved by means of a pintle. The displacement can be varied by changing the eccentricity of the housing.

Pumps of this type operate at high speeds, ranging from about 7,000 rpm for a 35-gpm unit to nearly 20,000 rpm for pumps with 2- to 8-gpm output ratings (Ref. 1). One advantage of the spherical-piston pump is a relatively high power-to-weight ratio.

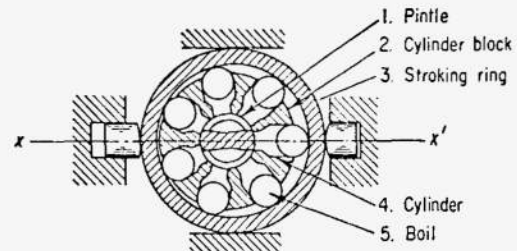


Fig. 2-12. Radial-piston Hydraulic Pump With Spherical Pistons

[From: E. C. Fitch, *Fluid Power and Control Systems*¹. Used by permission of McGraw-Hill, Inc.]

2-2.3.3 Rotating Piston Pumps

The rotating piston pump (sometimes called the rotary abutment pump) has three parallel synchronous shafts (Fig. 2-13). Piston rotors are mounted on the outside shafts and seal dynamically against the cylindrical housing. The rotor mounted on the center shaft forms an abutment valve. The rims of the piston rotors pass through a bucket cut in the center rotor. Except when the rim is meshed with the abutment valve, a rolling-contact seal is maintained between the rotors. Liquid is drawn into the right cylinder shown in Fig. 2-13, pumped through to the left cylinder, and discharged by the left piston. Pumps of this type are available with ratings to over 150 gpm at 1,500 psi.

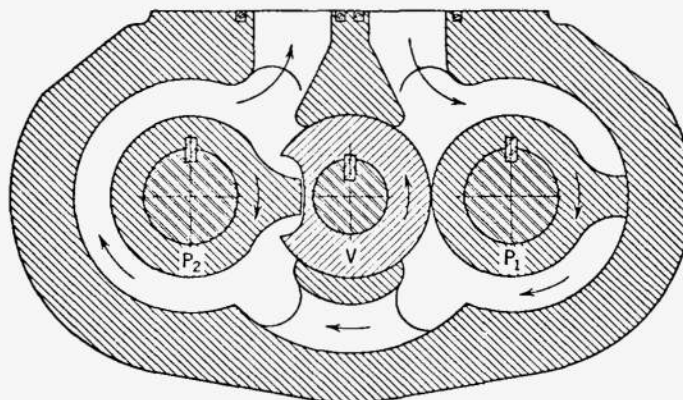


Fig. 2-13. Rotating Piston Hydraulic Pump [Shown are two rotating pistons P_1 and P_2 , and rotating abutment V.]

[From: H. E. Merrit, *Hydraulic Control Systems*⁴. Used by permission of John Wiley and Sons]

2-2.4 SCREW PUMPS

A screw pump is an axial-flow gear pump. Fig. 2-14 shows a two-rotor screw pump with helical gears. Liquid is introduced at the two ends and discharged at the center. The seal is formed by the contact of the two gears at the intersection of their addenda and by the small clearance between the gears and the pump housing. In pumps employing double helical gears, as shown in Fig. 2-14, the thrust loads are balanced. This design is frequently employed in large pumps. Screw pumps are especially applicable where quiet operation is essential. In screw pumps, the gears must be in contact at the intersection of their addenda. This contact plus the minimum clearance at the outside diameter of the gears, provides a series of sealed chambers along the length of the screws. Screw pumps can also be arranged with three rotors. The center gear is the driver, and no timing gears are necessary.

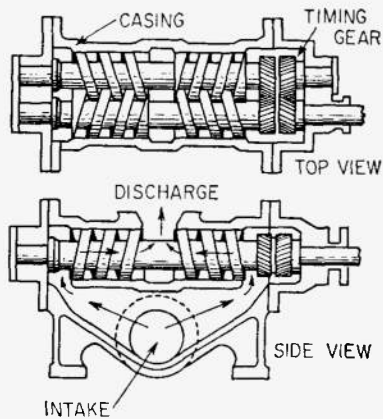


Fig. 2-14. Two-rotor Screw Hydraulic Pump With Helical Gears

[From: Pippenger and Hicks, *Industrial Hydraulics*². Used by permission of McGraw-Hill, Inc.]

2-2.5 BELLOWS PUMPS

A sketch of a typical bellows pump is shown in Fig. 2-15. The bellows is constructed of thin flexible metals or elastic nonmetals. Compression of the bellows by the actuator provides the pumping action. Liquid flow is controlled by check valves at the inlet and outlet ports. Bellows pumps are not generally used in hydraulic systems and find only limited applications in other fields. One area of application has been the medical field where they have the advantage of simple construction and are easily fabricated of inexpensive disposable

materials. Bellows pumps also are very effective pumps for liquids that are contaminated with solid particle material, and for abrasive slurries. There are no small clearance areas for the particles to damage or clog.

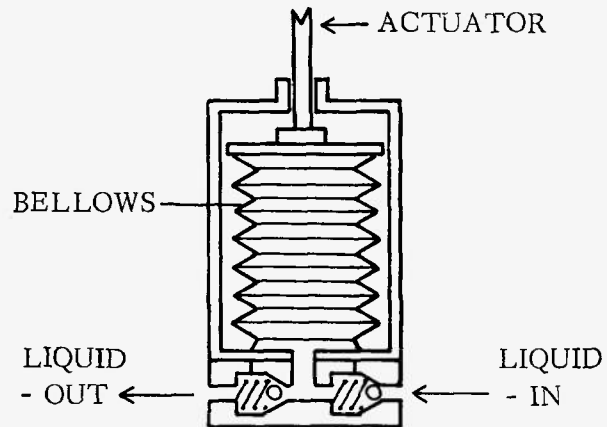


Fig. 2-15. Typical Bellows Pump

2-2.6 DIAPHRAGM PUMPS

A sketch of a typical diaphragm pump is shown in Fig. 2-16. The diaphragm is a flexible disk attached about its circumference to the pump housing. The actuator moves the diaphragm in a reciprocating motion which provides the pumping action. Diaphragms can be flexible sheets of metal or elastic nonmetals. Liquid flow is controlled by check valves at the inlet and outlet ports. Diaphragm pumps are primarily low pressure, pulsating flow pumps and are not often used for hydraulic power sources. Diaphragm pumps are occasionally used as hydraulic power sources where a remote pump is required—such as in high-temperature or corrosive environments. The valve head, containing the inlet and outlet valves, can be located in the hostile environment and the diaphragm unit located in a remote place. One of the most common uses of diaphragm pumps is the fuel pump on automobiles.

Diaphragm pump advantages include simple construction, no lubrication problems, high volumetric efficiency, and insensitivity to contamination. Major disadvantages are the low pressures obtainable, pulsating flow, and low flow rates.

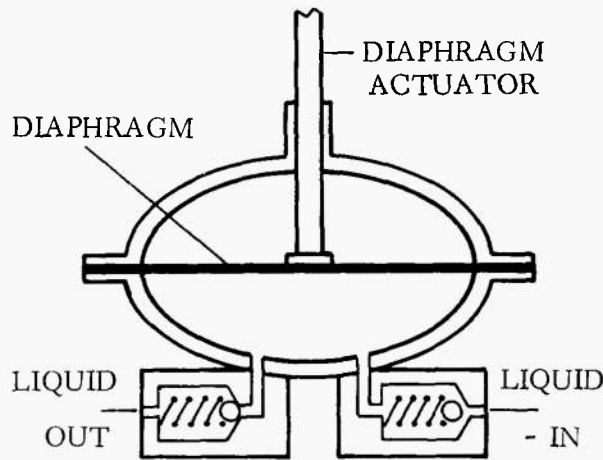


Fig. 2-16. Typical Diaphragm Pump

2-2.7 CONNECTION BETWEEN PUMP AND DRIVE MOTOR

The physical connection between the hydraulic pump and its drive motor is not technically a hydraulic component. However, it is an important part of the hydraulic system, and in many cases, may be the weakest link in the power train. There are a number of methods for coupling the drive motor output shaft to the hydraulic pump input shaft. Some of the more common methods are keys and pins, flexible couplings, universal joints, clutches, and splines. The most frequently used connector in hydraulic systems is the spline.

Splines offer the advantage of being able to transmit the maximum load with the smallest coupling diameter. In addition, they are self-centering, tend to equally distribute the load, and are simple to manufacture with standard gear-cutting equipment. Their major disadvantage is the problem of wear. Even the best designed splines are subject to relative motion of the parts and are difficult to lubricate.

2-3 ACTUATORS

An actuator is a device for converting hydraulic energy to mechanical energy, and thus has a function opposite that of a pump. An actuator, or fluid motor, can be used to produce linear, rotary, or oscillatory motion.

2-3.1 LINEAR ACTUATORS

A linear actuator or hydraulic cylinder is a fluid motor that generates linear motion. Various types are widely used in hydraulic systems because of their high force capability, ease of speed control, and high power output for a given size and weight. They are especially suitable for control systems due to their high mechanical stiffness and speed of response.

2-3.1.1 Classification of Linear Actuators

The many types of linear actuators which are available give rise to several criteria for classification.

(1) *Rotating or nonrotating:* In a rotating actuator the cylinder, rod, and piston can rotate. In many applications, such as on rotary machine tools, this feature is necessary to allow unrestricted motion of the piston rod. Such an actuator is illustrated in Fig. 2-17. In order to permit stationary mounting of the fluid connections, a rotating seal is required.

The nonrotating linear actuator, in which the cylinder is not free to rotate, is the most widely used fluid motor.

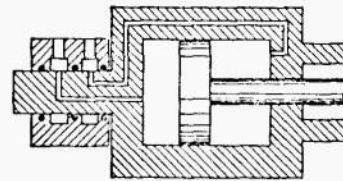


Fig. 2-17. Rotating Linear Actuator

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹ Used by permission of McGraw-Hill, Inc.]

(2) *Piston or plunger:* The piston and rod assembly in a piston-type linear actuator serves to divide the cylinder volume into two separate chambers. The piston and attached sealing devices provide the seal between the two chambers. The rotating actuator shown in Fig. 2-17 is a piston actuator.

In a plunger-type there is no piston. The end of the reciprocating rod serves as the working face (see Fig. 2-18). The only seal provided is at the point where the plunger passes through the end of the cylinder. An external force is required to move the plunger into the cylinder.

Both types provide a longer stroke and permit the use of the highest pressure.

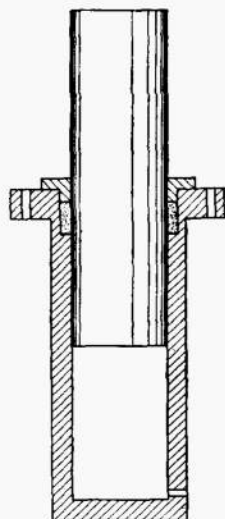


Fig. 2-18. Plunger-type Linear Actuator

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹
Used by permission of McGraw-Hill, Inc.]

(3) *Rod classification:* Linear actuators can also be classified as to rod type. A cylinder with one piston rod is termed a single-rod actuator. The actuators shown in Figs. 2-17 and 2-18 are single-rod actuators. A double-rod actuator has piston rods extending from both ends of the cylinder. A telescoping rod consists of a series of nested rods which provide a long extension (Fig. 2-19). Such rods are useful for applications requiring a long stroke but with only limited space available for the unextended rod. A positional rod is used where the stroke is split up into two or more portions. The cylinder can be actuated to any one of the positions.

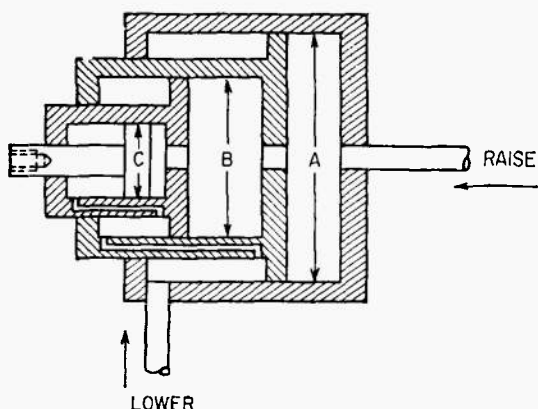


Fig. 2-19. Telescoping Linear Actuator

[From: Pippenger and Hicks, *Industrial Hydraulics*.²
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(4) *Cylinder action:* The type of cylinder action is important in the specification of linear actuators. An actuator can be single-acting or double-acting. The single-acting type can move the piston rod in only one direction by the application of hydraulic pressure. A plunger-type actuator, discussed in subparagraph 2-3.1.1(2), is a single-acting actuator. In the double-acting actuator, liquid pressure can be applied to either side of the piston, thereby providing a hydraulic force in both directions (Fig. 2-20). Double-acting actuators are also shown in Figs. 2-17 and 2-19. Springs, external forces, or a combination of both can be used to assist return of the piston rod or plunger.

DOUBLE-ACTING CIRCUIT
(THRUST IN BOTH DIRECTIONS)

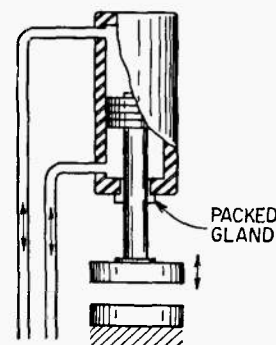


Fig. 2-20. Double-acting Linear Actuator

[From: Pippenger and Hicks, *Industrial Hydraulics*.²
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(5) *Single, tandem, and dual actuators:* Yet another means of actuator classification is its assembly. Assemblies of actuators can be designed to obtain various types of cylinder operation. A tandem actuator is one in which two or more piston and rod combinations are assembled as a rigid unit with all pistons mounted on a single rod. Fig. 2-21 shows a stepped-tandem actuator—two pistons of different sizes mounted on one rod. Such actuators can be designed to obtain, for example, a low-force, high-speed action followed by a high-force, low-speed action. Tandem pistons can also be designed to provide a large working area (and thus large forces for a given pressure) for a small cylinder diameter. The piston and rod assemblies of a dual actuator (Fig. 2-22) are not fastened together as in the tandem actuator. In most dual actuator designs, a given piston acts on another only in one direction. Tandem and dual actuators are frequently used in hydro-pneumatic systems where air is used as the power source and a hydraulic fluid is used for control.

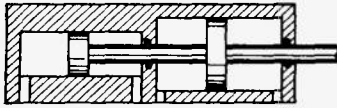


Fig. 2-21. Stepped-tandem Linear Actuator

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹
Used by permission of McGraw-Hill, Inc.]

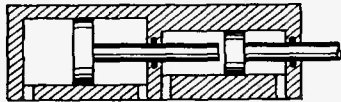


Fig. 2-22. Dual Linear Actuator

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹
Used by permission of McGraw-Hill, Inc.]

(6) *Cushioned or noncushioned type:* In noncushioned actuators, no provision is made for controlled acceleration or deceleration of the piston assembly. Therefore, such units have speed and inertia limitations imposed at both ends of the stroke. Cushioned actuators are designed to enable the kinetic energy of the moving piston to be absorbed at the ends of the stroke and thereby reduce peak pressures and forces. Cushioning can be accomplished by blocking the discharge

ports as the piston nears the end of the stroke (Fig. 2-23). A cushion-plunger attached to the piston enters a cushion cylinder. This cushion plunger then blocks the discharge port and traps liquid beneath the piston. This liquid assists in the deceleration of the piston as it approaches the cylinder head. A check valve allows fluid to flow back into the cylinder at the start of the return stroke. The rate of piston deceleration can be controlled by designing the cushion plunger with a proper taper. This taper then permits a gradual closing of the discharge ports.

2-3.1.2 Mounting Configuration

One of the advantageous features of linear actuators is the variety of ways in which they can be mounted in a system. Several mounting arrangements are illustrated in Fig. 2-24.

2-3.1.3 Kinematics of Linear Actuators

The nature of the force provided by a linear actuator depends on the kinematic linkage between the straight-line output of the cylinder and the point at which the force and motion are utilized. Because of the many alternatives in the design of the linkage, the linear actuator can be used to produce rotary or oscillatory motion as well as linear motion. The resultant versatility of linear actuators is partially illustrated by the applications shown in Fig. 2-25.

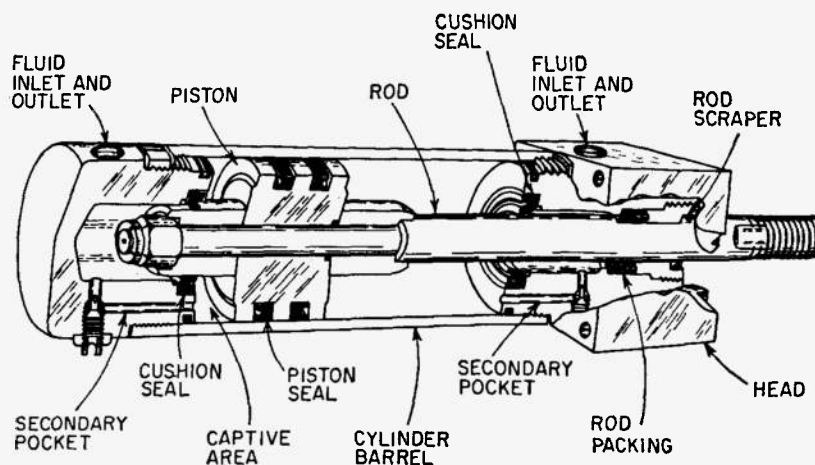


Fig. 2-23. Cushioned Double-acting Linear Actuator

[From: Pippenger and Hicks, *Industrial Hydraulics*.² Used by permission of McGraw-Hill, Inc.]

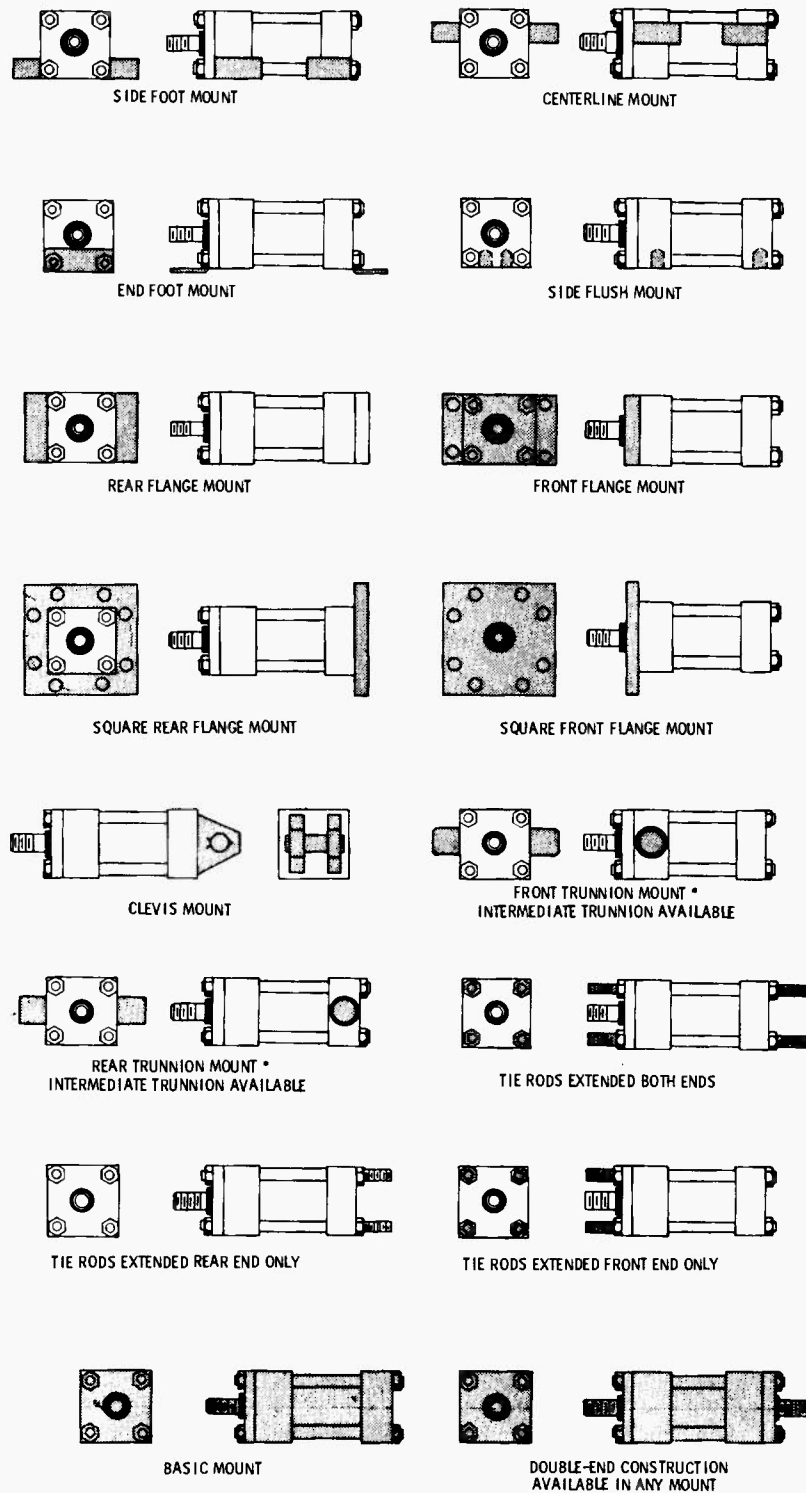


Fig. 2-24. Mounting Arrangements for Linear Actuators

[From: Stewart and Storer, *Fluid Power*³. Used by permission of Howard W. Sams and Co., Inc.]

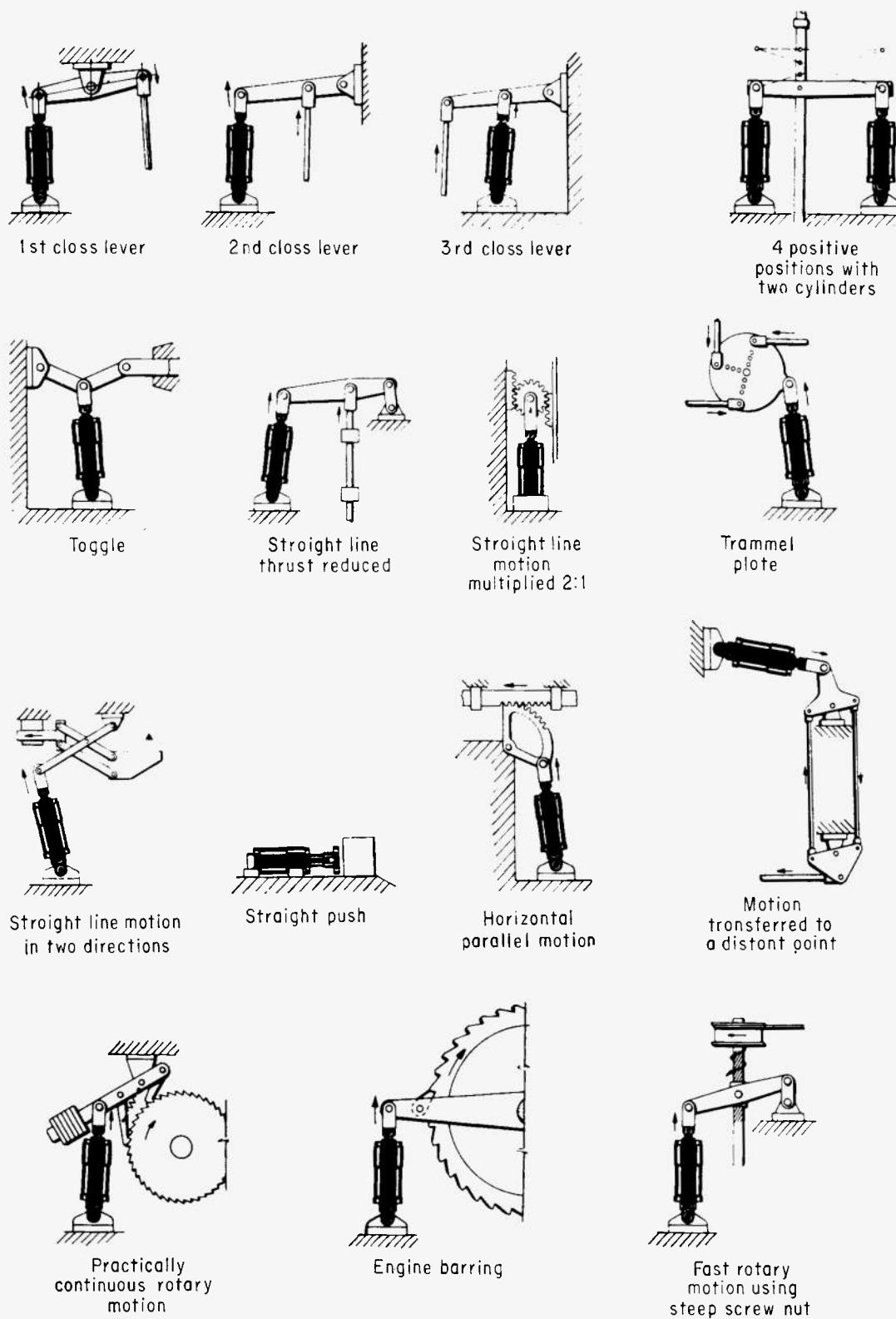


Fig. 2-25. Applications of Linear Actuators

[From: E. C. Fitch, *Fluid Power and Control Systems*¹. Used by permission of McGraw-Hill, Inc.]

2-3.2 ROTARY ACTUATORS OR MOTORS

As in the case of a linear actuator, the function of a rotary actuator, or rotary fluid motor, is to convert hydraulic energy into mechanical energy. Rotary motors are usually rated in terms of the theoretical torque developed per 100 psi of inlet or differential pressure. The actual running torque and the stalled torque may be from 60 to 90 percent of the theoretical torque, depending on the type of motor. The running volumetric efficiency may vary from about 75 to 95 percent, again depending on the particular motor. The highest operating efficiency occurs near the rated torque and speed.

The desirable features of the various types of rotary motors include:

- (1) The ability to suddenly start, stop, and reverse without motor damage
- (2) The ability to operate as a pump for braking
- (3) A higher horsepower-to-weight ratio than any other conventional power source
- (4) An infinitely-variable speed range
- (5) The ability to operate through zero speed for overrunning loads
- (6) The ability to accommodate contaminants in the fluid.

Rotary fluid motors are essentially rotary pumps operating in reverse. The mechanical characteristics of a particular rotary motor are nearly identical with those of the corresponding pump.

2-3.2.1 Gear Motors

Gear motors, like gear pumps, can be classified as external or internal gear units. Also like gear pumps, they are fixed-displacement devices. External gear motors include the gear-on-gear units such as the spur gear motor. Internal gear motors include the crescent seal types and the gerotor-type unit.

(1) *Gear-on-gear motors:* In the gear-on-gear motor, rotary motion is produced by the unbalanced hydraulic forces on the gear teeth which are exposed to the inlet pressure. An example is the spur gear motor which has the same mechanical features as the spur gear pump shown in Fig. 2-2. These units are applicable for peak operating pressures up to about 1,500 psi and are available with rated capacities up to 120 gpm, maximum speeds of about 3,000 rpm, and power ratings up to approximately 50 hp. Bearing loads generated by the hydraulic unbalance are high, as in the case with unbalanced gear pumps. Typical operating curves for spur gear motors are given in Fig. 2-26.

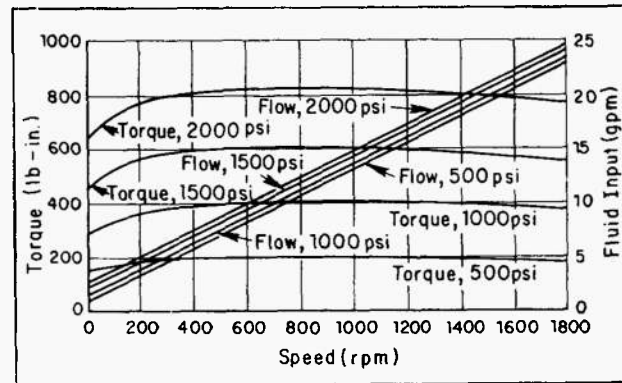


Fig. 2-26. Typical Operating Characteristic Curves for a Spur Gear Hydraulic Motor

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

(2) *Crescent seal motors:* The crescent seal motor employs an inner and outer gear with a crescent-shaped seal separating the teeth during part of the revolution. Its operational features are the reverse of those of the crescent seal pump illustrated in Fig. 2-4. Motor units of this type are suitable for high-speed, low-power operations at low-to-moderate pressure. Starting torque and running efficiencies are low. Typical operating curves for crescent seal motors are shown in Fig. 2-27.

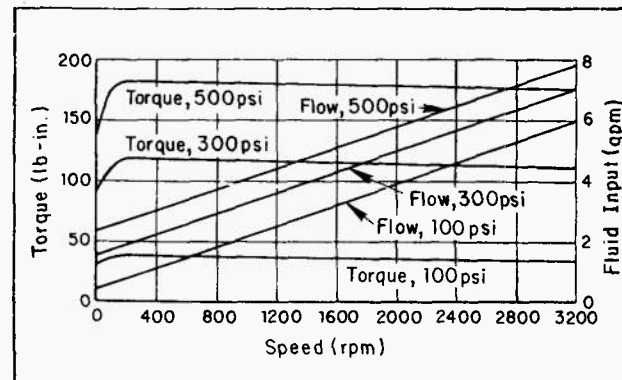


Fig. 2-27. Typical Operating Characteristic Curves for a Crescent Seal Hydraulic Motor

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

(3) *Gerotor-type motors:* The gerotor motor (see Fig. 2-5 for corresponding pump) is suitable for high-speed operation and exhibits relatively high starting-torque efficiency. It can be used for operating pressures up to about 2,000 psi. Volumetric efficiency is relatively

low and leakage rates are high at most speeds. The cost of gerotor motors is relatively high in comparison with the other gear motors. The operating curves of Fig. 2-28 are typical of the gerotor motor.

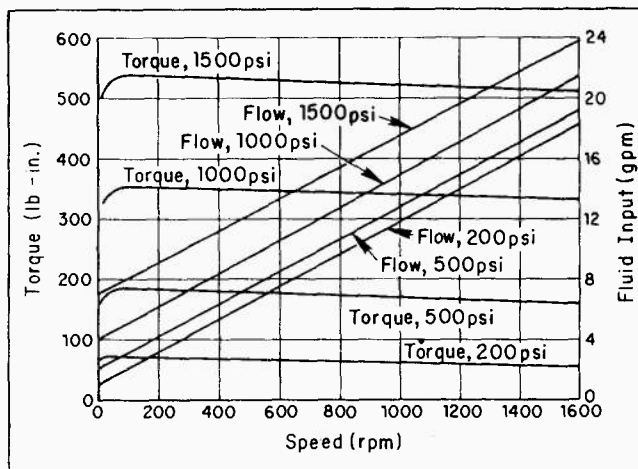


Fig. 2-28. Typical Operating Characteristic Curves for a Gerotor Hydraulic Motor

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

2-3.2.2 Vane Motors

Most vane motors are of the balanced-rotor type because hydraulic unbalance causes large radial bearing loads which limit the use of unbalanced vane motors to low pressure operation and applications where weight and space considerations do not preclude the use of large, heavy bearings. Therefore, most vane motors have a mechanical configuration similar to that of the balanced vane pump shown in Fig. 2-9 and are thus fixed-displacement units. To accommodate starting and low-speed operation, it is usually necessary to provide a force—in addition to the centrifugal force—to move the vane radially outward. Springs are commonly used for this purpose.

As with vane pumps, rolling and swinging vanes can also be used in vane motor design (see Fig. 2-8). The overall running efficiencies of vane motors are typically 80 to 85 percent. They are available at rated powers up to approximately 125 hp, pressure ratings to about 2,500 psi, and maximum speeds of approximately 3,000 rpm. Characteristic operating curves of a vane motor are shown in Fig. 2-29.

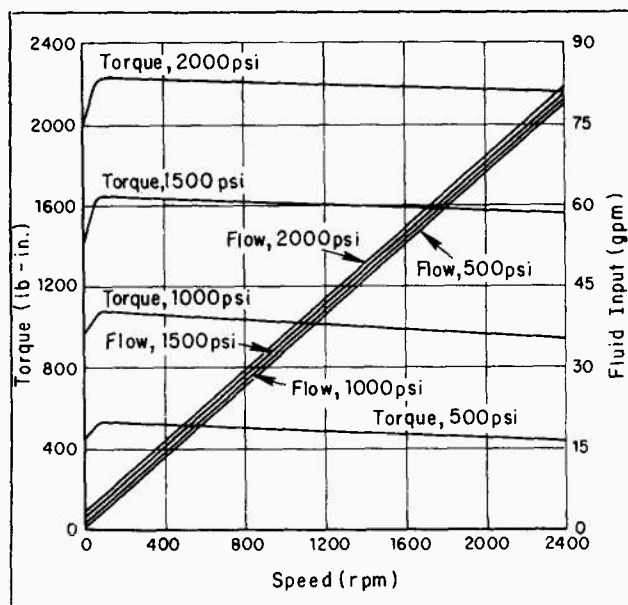


Fig. 2-29. Typical Operating Characteristic Curves for a Vane Hydraulic Motor

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

2-3.2.3 Limited-rotation Motors

Limited-rotation motors, or rotary actuators, provide an oscillating power output. A variety of such units is available, all of which consist of one or more fluid chambers and a movable surface against which the fluid pressure is applied. Both vane-type and piston-type motors can be used to obtain an oscillatory output.

(1) *Vane type*: There are two types of limited-rotation vane motors, the single-vane and the double-vane. The single-vane unit consists of a cylindrical housing, a shaft with a single vane, a barrier which limits the vane rotation, and end pieces which support the shaft (Fig. 2-30). High-pressure liquid enters on one side of the vane, forcing the vane to rotate to the barrier. A rotation of approximately 280 deg can be obtained with the single-vane unit. In the double-vane unit, the high-pressure fluid enters on one side of a vane and is ported through the shaft to the corresponding side of the other vane (Fig. 2-31). A rotation of about 100 deg is possible with the double-vane motor. In both the double- and the single-vane units, seals are maintained between the rotor and the barriers and between the vanes and the housing. Limited-rotation vane motors are available with torque outputs ranging from less than 10 in.-lb at about 50 psi to nearly 750,000 in.-lb at 3,000 psi.

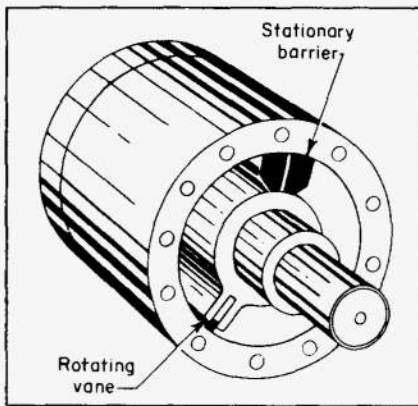


Fig. 2-30. Typical Single-vane Actuator

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

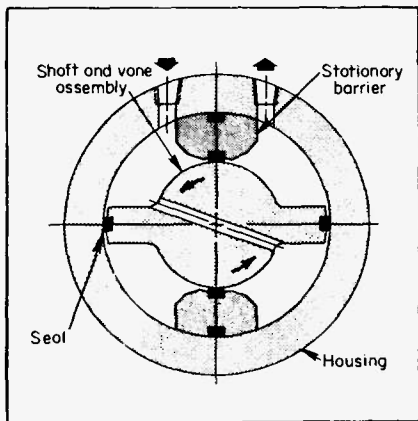


Fig. 2-31. Typical Double-vane Actuator

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

(2) *Piston type*: Piston-driven actuators are available in several configurations designed to produce an oscillating output. The helix-spline unit employs a shaft with a helical screw which passes through the piston (Fig. 2-32). A guide rod prevents rotation of the piston. Rotations of greater than 360 deg are possible. A self-locking helix angle prevents rotation when an external torque is applied. The piston-rack unit consists of two or more pistons which provide the rack for a rack-and-pinion system (Fig. 2-33). Many variations of the latter design are available.

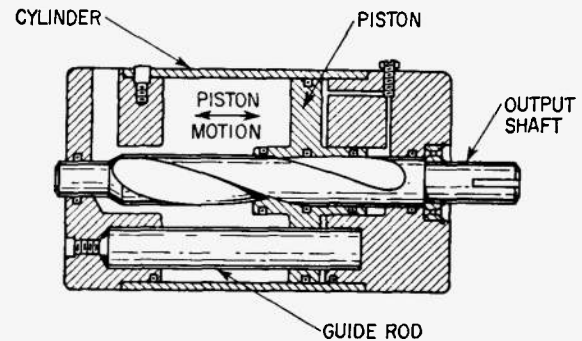


Fig. 2-32. Helix-spline Rotary Actuator

[From: Pippenger and Hicks, *Industrial Hydraulics*². Used by permission of McGraw-Hill, Inc.]

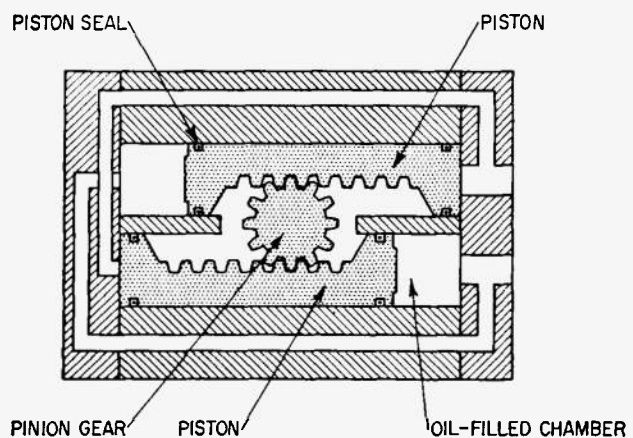


Fig. 2-33. Piston-rack Rotary Actuator

[From: Pippenger and Hicks, *Industrial Hydraulics*². Used by permission of McGraw-Hill, Inc.]

2-3.2.4 Piston Motors

Piston motors which generate a continuous rotary output motion (as opposed to linear actuators) can be classified in terms of the piston motion—axial, radial, or rotary. They can be fixed- or variable-displacement devices. They can operate at high pressures and have high volumetric efficiencies. The power-to-weight ratio of piston motors is not as favorable as that of gear and vane motors, but piston units are available with power outputs greater than 300 hp. Relative cost per horsepower is high.

(1) *Axial-piston type*: The operation of an axial-piston motor is essentially the same as that of an axial-piston pump except for the direction of flow (see Fig. 2-10). The high-pressure liquid introduced through the

motor inlet forces the piston assembly against the thrust cam or wobble plate. The angular application of this force causes the plate to rotate and this rotation is transmitted by the shaft. The displacement can be varied by changing the angle of the thrust cam. Leakage is low under both running and stalled conditions.

(2) *Radial-piston type*: The radial-piston motor is also essentially its pump counterpart operating in reverse (Fig. 2-11). Liquid enters the piston chamber through a central pintle. The piston is forced radially outward against the thrust ring, thereby producing a force tangent to the piston chamber. The resulting torque causes the shaft to rotate. This motor type exhibits very high volumetric efficiencies and high torque, and is well-suited for low-speed application because of the small mass of the rotating parts.

(3) *Rotary-piston type*: The rotary-piston motor is the same as the rotary-piston pump except for the flow direction. The pump was described in par. 2-2.3.3. Units are available with a rating of up to 300 hp at 2,800 rpm with a maximum torque of over 20,000 in.-lb. Weight and space-to-power ratios are high, and cost per horsepower is usually high.

2-3.3 FLUID TRANSMISSIONS

A fluid transmission is a device which converts mechanical power into fluid power, transports this power, and then converts it back into mechanical power. Therefore, the circuit consists of some suitable combination of pump and motor with the necessary piping. The transmission characteristics depend on the pump and motor combination. The various possible combinations are outlined in the paragraphs which follow. Assumptions made are that the pump outlet and motor inlet pressure are the same; a constant output pressure is maintained on variable-displacement pumps; and the pump speed is constant. Fixed-displacement pumps are assumed to have relief valves.

(1) *Fixed-displacement pump and motor*: The torque and horsepower of the pump are functions of the pressure but the speed and flow rate are usually constant. Below the relief-valve setting, the motor torque and horsepower vary with pressure while the speed and flow rate are constant. At or above the relief-valve pressure, the motor torque is constant, but motor speed and flow rate are functions of the volume flow rate through the relief valve. The resulting transmission exhibits constant speed with variable torque and horsepower below the relief valve pressure, and constant torque with variable speed and horsepower at higher pressures.

(2) *Fixed-displacement pump and variable-displacement motor*: The pump operates as described in par. 2-3.3(1). The torque of the motor varies inversely with speed. Motor flow rate is a function of both displacement and relief-valve flow. The transmission produces constant horsepower and a torque which varies with speed.

(3) *Variable-displacement pump and fixed-displacement motor*: The pump pressure and speed are constant, but the torque and horsepower vary. The motor pressure and torque are constant while the speed and horsepower vary. The resulting transmission has constant torque. The horsepower varies with speed.

(4) *Variable-displacement pump and motor*: The pump operates as in the preceding case. The motor torque and speed are inverse functions of the displacement. The torque and horsepower transmitted by the system can be constant or variable.

2-4 INTENSIFIERS

A liquid intensifier—used only in single cylinder applications—is a device used to compress the liquid by a pressure greater than the system pressure generated by the primary pump. This is accomplished by using different piston working areas to boost the pressure. The increase in pressure obtained in the simple intensifier shown in Fig. 2-34 is directly related to the area ratio of the pistons. The high-pressure piston is attached to the same rod as the larger low-pressure piston. When the control valve is in the neutral position, the liquid, which is at system pressure, is directed to a reservoir. If the left solenoid is actuated, fluid is introduced to the rod side of the low-pressure piston and into the chamber on the downstream side of the high-pressure piston. The piston assembly moves to the right, returning the fluid in the low-pressure chamber to a reservoir. The intensifier is then ready for a working stroke. When the right solenoid is energized, fluid is introduced into the low-pressure chamber. The piston assembly is driven to the left, compressing the fluid in the high-pressure chamber. Because of the reciprocating pumping action, the intensifier produces a pulsating high-pressure flow. The high-pressure flow rate is less than the system flow rate by the same ratio as that of system pressure to boosted pressure.

In circuits which require high-volume, low-pressure flows—as well as smaller high-pressure flow over short periods—the fluid intensifier offers an economic alternative to the necessity of providing two primary power sources. The intensifier has several additional advantages. A low power input can be used to maintain a

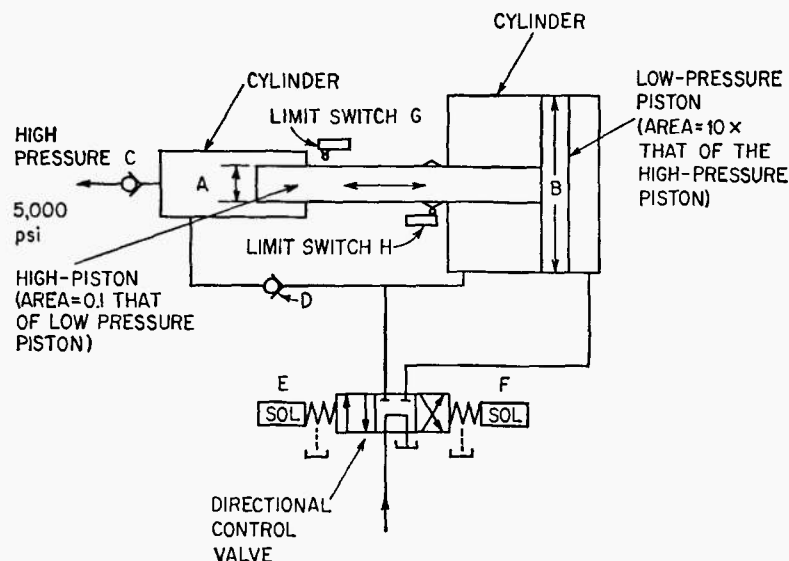


Fig. 2-34. Diagram of a Hydraulic Intensifier Circuit

[From: Pippenger and Hicks, *Industrial Hydraulics*². Used by permission of McGraw-Hill, Inc.]

high pressure for a period of time. The high-pressure regions of the circuit can be localized, thereby reducing the amount of high-pressure piping and the number of high-pressure seals required. Because of the seal between the high- and low-pressure chambers, the intensifier can be operated with a liquid different from that used in the high-pressure part of the circuit. Since no heat is generated while static pressure is maintained and little heat is generated during rapid cycling, only small reserves of oil are required.

2-5 RESERVOIRS

2-5.1 FUNCTION

Reservoirs not only provide a storage facility for the liquid but can also serve to separate entrained air, remove contaminants, and dissipate heat from the liquid. Thus, along with heat exchangers and filters, the reservoir is an important liquid-conditioning component.

2-5.2 CAPACITY

Even before the conditioning functions of the reservoir are considered in design, the necessary capacity

must be determined. The size and configuration depend on many factors. The minimum required capacity can vary from one to three times the volumetric rating of the pump in gallons per minute. The reservoir should be sufficiently large to accommodate the liquid necessary to fill all system components if the liquid drains back to the reservoir. It should have sufficient capacity to maintain a liquid supply at the pump suction at all times. Sufficient liquid should be in the system to prevent the formation of vortices at the pump suction. Reservoir volume should be provided to allow time for solid contaminants and gases to separate from the liquid. This factor also depends on both the characteristics of the liquid and filtering system design. Adequate space above the liquid level should be provided to accommodate thermal expansion of the liquid. If the reservoir serves as the primary means of dissipating heat from the liquid, it should be large enough to accommodate the required cooling. In some applications, the liquid in the reservoir is intermittently used as a heat sink. It is then necessary to provide storage for enough liquid to give the desired heat capacity. For operation in cold environments excessive cooling can also be avoided by proper reservoir capacities.

2-5.3 DESIGN

There are three basic reservoir arrangements—separate, integral, and dual-purpose. Separate reservoirs are

commonly used in large stationary systems where space and weight are not important considerations. Integral reservoirs are spaces provided within the hydraulic system—such as piping, tubular structural members, or machine bases. Such a design minimizes space and weight requirements. However, the storage of a hot liquid within the system can sometimes cause thermal distortion of precision components. If the liquid can serve as both a lubricant and a hydraulic fluid, individual reservoirs are not required. The reservoir in which such a liquid is stored is termed a dual-purpose reservoir. For example, the case which houses the transmission in some vehicles, and which thus contains the transmission lubricant, also serves as the hydraulic fluid reservoir. In such applications it is, of course, necessary that the liquid function satisfactorily both as a lubricant and as a hydraulic fluid. Also, since the liquid absorbs heat from two sources, it may be difficult to provide adequate cooling.

Many of the guidelines which assist in the design of reservoirs are the same regardless of the reservoir type. Baffles should be provided between the suction line and the fluid-return lines to prevent continual use of the same liquid. Baffles also reduce the liquid velocity and thereby facilitate the settling of solid contaminants and deaeration of the liquid.

Lines which return liquid to the reservoir should be well below the liquid level to minimize aeration. Suction lines should also terminate below the minimum liquid level, but the inlet should be at least 1-1/2 pipe diameters above the tank floor. If the suction line strainer is not sufficiently beneath the liquid level at all times, a vortex could form and permit air to enter the suction line. Gravity drains from seal cavities should be separate from the liquid return lines and should enter the reservoir above the liquid level.

Ample provision must be made for draining and cleaning. Liquid-level indicators should be provided to indicate the maximum and minimum allowable liquid levels. An air breather and filter allow air to enter or leave the reservoir as the liquid level fluctuates. Some reservoirs are pressurized to assist pump suction.

2-6 FILTERS

The ability to keep the liquid clean is a very important factor in the long-term operation of a hydraulic system. To minimize contaminant levels, foreign matter should be prevented from entering the system; conditions conducive to contaminant formation within the system should be avoided; and filters should be used to remove contaminants.

Filters are rated in terms of the degree of filtration. The ratings are usually expressed in microns (1 micron = 3.937×10^{-5} in.). If a filter can remove 98 percent of the particles of a certain size or larger, then this particle size, expressed in microns, is termed the *nominal* filtration value. The *absolute* filtration value is the size of the smallest particle which the filter can completely remove from the flow. Filters are usually rated in terms of both nominal and absolute values. It is common practice to specify filters with an absolute filtration value equal to one-half of the smallest clearance or tolerance in the components which the filter must protect.

2-6.1 CLASSIFICATION OF FILTERS

Filters are classified according to the filter media, the configuration, or the filtering method. The filter media can be either the surface-type or the depth-type. The surface-type filtering media contain numerous orifices of relatively uniform size. Particles larger than the orifice size are trapped on the surface of the media. Depth-type media have long tortuous paths through which the liquid must flow. Particles larger than the cross section of these flow paths are retained except perhaps for some particles which are larger in only one dimension. Wire mesh is an example of a surface filter medium. Depth media include sintered metal powders and fibrous materials such as paper, felt, glass, and cellulose. Classification by filter media is closely related to classification by filtering method, which is discussed in par. 2-6.2.

There are five basic filter configurations (see Fig. 2-35). The T-type filter is the most widely used unit because it is compact and easy to clean or replace. By-pass reliefs and pressure-difference indicators are frequently incorporated to determine when a filter is clogged.

2-6.2 FILTERING METHODS

There are three basic physical mechanisms by which filters can remove contaminants from a hydraulic fluid—mechanical, adsorbent, and absorbent. The filtering methods sometimes function in combination.

2-6.2.1 Mechanical Filters

In a mechanical filter, particles are removed from the hydraulic fluid by virtue of their inability to pass

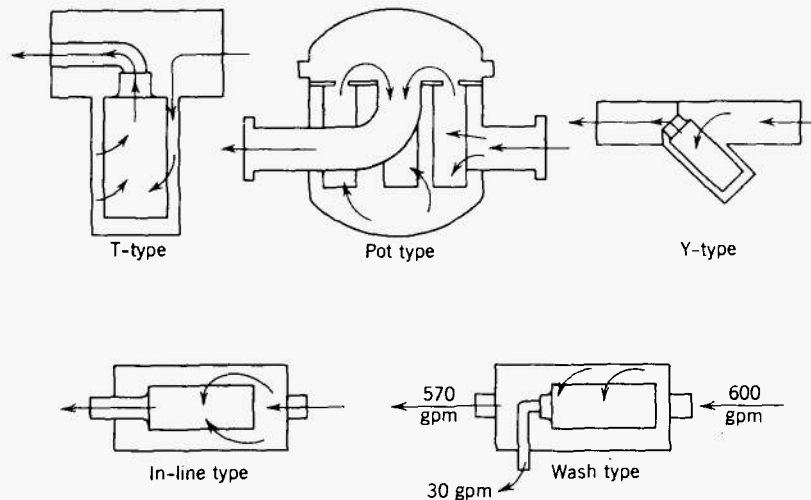


Fig. 2-35. Basic Configurations of Filter Assemblies

[From: H. E. Merrit, *Hydraulic Control Systems*.⁴ Used by permission of John Wiley and Sons]

through the multitude of small holes or orifices in the filter. Metal or fabric screens are commonly used as the filter media. The disk-type filter shown in Fig. 2-36 is also a mechanical filter. The size of particles which can be removed by this filter depends on the spacing

between the disks. The filter can be cleaned while in service by revolving the central shaft to which alternate disks are keyed. The stationary elements then act as wipers. Wire-screen mechanical filters can also be cleaned if care is taken not to force contaminant particles inside or through the elements.

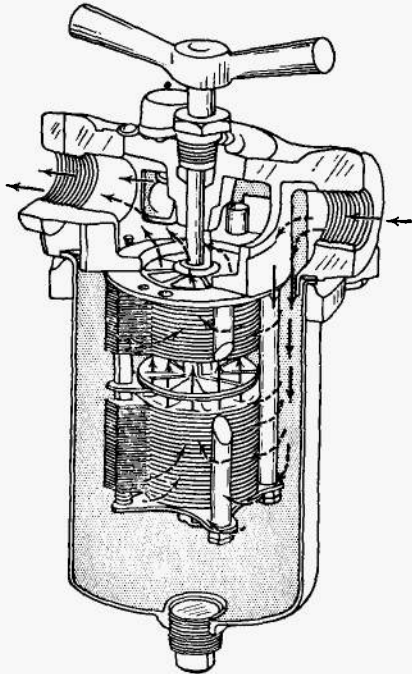


Fig. 2-36. Hydraulic Fluid Filter With Disk-type Filter Elements

[From: Pippenger and Hicks, *Industrial Hydraulics*.² Used by permission of McGraw-Hill, Inc.]

2-6.2.2 Adsorbent Filters

Adsorption is the phenomenon by which particles of one material tend to adhere to solid or liquid surfaces. The filter medium in an adsorbent-type filter is finely divided to present maximum surface area to the flow. Materials used in the filter elements include activated clay, charcoal, fuller's earth, chemically treated paper, and bone black. The flow passages of the filter can also mechanically remove contaminants. One disadvantage of the adsorbent filter is the tendency to remove certain additives in the hydraulic fluid. Hence, it is not usually recommended for service with fluids which contain additives. Many adsorbent filter housings are designed to accommodate either an adsorbent filter element or a mechanical filter element.

2-6.2.3 Absorbent Filters

A porous, permeable medium is used as an element in an absorbent filter. Element materials include diatomaceous earth, wood, pulp, asbestos, paper, various textiles, and a variety of other substances. As the

hydraulic fluid passes through the filter medium, contaminants are trapped by absorption. Water and water-soluble contaminants can be removed by some absorbent filters. The size of solid contaminant which can be filtered depends upon the permeability and porosity of the filter element.

2-6.3 HYDRAULIC FLUID-FILTER COMPATIBILITY

The hydraulic fluid filter must not be affected by the hydraulic fluid at any operating condition. Also, the filter must not have any effect on the hydraulic fluid—such as removing additives in the liquid. Filter compatibility is not often a problem with pure mechanical-type filters. In this case it is only necessary to use a filter element made of materials (usually metal) that are compatible with the particular hydraulic fluid. This is not the case, however, when absorbent- or adsorbent-type filters are used. In addition to their mechanical filtering action, these filters also have a chemical filtering action. The chemical action may result in the removal of additives as well as impurities and contaminants. Because additives are usually included to improve properties of the liquid, their removal is not desirable. Special consideration must be given to the use of these filters when the hydraulic fluid is not a straight unmodified base stock.

2-6.4 FILTER PRESSURE DROP

The influence of pressure drop on filter selection involves a compromise between two conflicting factors. In order to filter small particles from a hydraulic fluid, the size of the filter passages must be small, and this results in high pressure drop. However, if the pressure drop is too high, contaminant particles can penetrate into or through the filter element. A pressure drop greater than 12 or 15 psi is usually sufficient to force the contaminants commonly found in hydraulic systems through a typical filter.

The pressure drop is a function of contaminant particle size, the fineness of the filter medium, the ability of the particle to resist the drag forces created by the flow, the rate at which particles accumulate in the filter, and the mechanical strength of the filter element. The pressure differential which can be tolerated across a filter also depends upon the location of the filter in the system. Allowable pressure drop is also an important factor in establishing the cleaning and service schedule of a filter.

2-6.5 REPLACEMENT OR CLEANING INTERVALS

Two approaches can be made to establish a maintenance program for hydraulic fluid filters. If instruments are provided to monitor filter operation, replacement or cleaning can be based upon the data obtained from these measurements. If no such data are available, it is necessary to establish a systematic maintenance program which specifies the operating intervals for each filter.

Pippenger and Hicks (Ref. 2) present the following guidelines on which to base a filter maintenance schedule:

- (1) Provide instruments to monitor filter saturation and indicate cleaning or replacement requirements
- (2) Stress the importance of the filters in the system operating procedure by instructing all operating and maintenance personnel in the filter locations, functions, and service schedules
- (3) Establish service procedures which minimize downtime and fluid loss
- (4) Maintain records of filter performance and use these to establish satisfactory filter service times
- (5) Evaluate filter performance to determine if different filters might improve the system operation.

2-7 ACCUMULATORS

An accumulator is a device which can store hydraulic energy. It is useful in intermittent operation of hydraulic machines when the accumulator can be charged at a low flow rate during the idle portion of the cycle of the driven machine. Accumulators can be used for pressure compensation, pulse damping, leakage compensation, emergency power, auxiliary pressure, and several other applications. They can also be used to apply pressure across a physical boundary between two liquids without contact or mixing of the liquids. This feature permits the pressurization of hazardous fluids, e.g., a volatile liquid, by means of a second liquid which can be safely pumped.

2-7.1 ACCUMULATOR LOADING

Accumulators are classified in terms of the manner in which the load is applied. This is the major factor which influences design. Accumulators can be weight-loaded, spring-loaded, or pneumatic-loaded.

2-7.1.1 Weight-loaded Accumulators

The weight-loaded accumulator consists of a piston mounted vertically in a cylinder (Fig. 2-37). The piston rod or plunger is loaded with weights which provide potential energy to compress the fluid. This accumulator produces virtually constant pressure at all fluid levels. However, weight-loaded accumulators are very heavy and expensive. They also do not respond quickly to changes in the system demand. For these reasons, they are not often used in modern hydraulic systems.

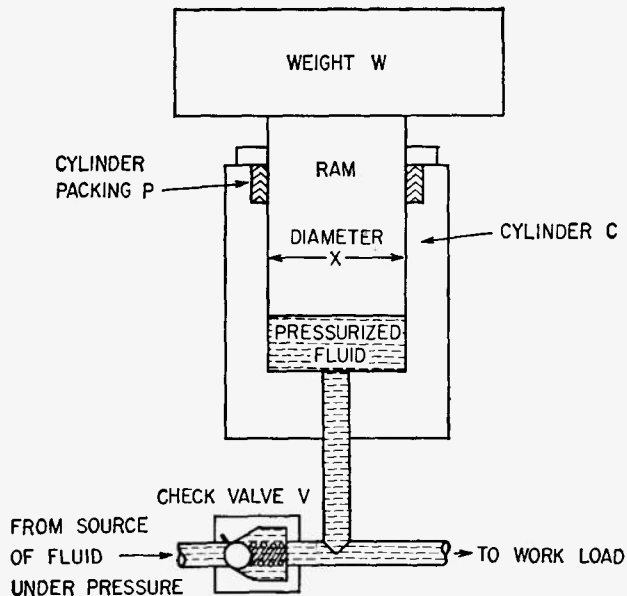


Fig. 2-37. Weight-loaded Hydraulic Accumulator

[From: Pippenger and Hicks, *Industrial Hydraulics*². Used by permission of McGraw-Hill, Inc.]

2-7.1.2 Spring-loaded Accumulators

An accumulator in which the compression energy is supplied by a spring is shown in Fig. 2-38. The pressure varies with the amount of fluid in the accumulator since the spring force depends on displacement. Although such spring-loaded devices are easy to maintain, they are relatively bulky and costly. Most applications are for low-volume, low-pressure systems.

2-7.1.3 Pneumatic-loaded Accumulators

There are two types of pneumatic-loaded accumulators. In one type, the gas which provides the load is in

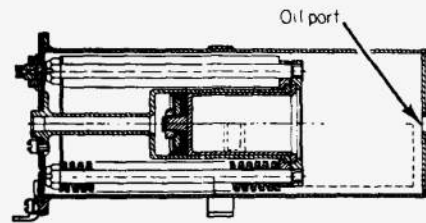


Fig. 2-38. Spring-loaded Hydraulic Accumulator

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

direct contact with the hydraulic fluid, whereas in the second type they are separated by a diaphragm, bladder, or piston.

(1) *Nonseparated-type*: Pressurization in a non-separated, pneumatic-loaded accumulator is achieved by introducing a pressurizing gas into a container above the liquid level. The pressurized storage vessel is a simple example of this type. Limit switches, which are actuated by liquid level, are usually used to limit pressure. This type can accommodate large liquid volumes, but aeration of the liquid often precludes their use in hydraulic systems. Fig. 2-39 shows a diagram of a non-separated pneumatic accumulator in a circuit.

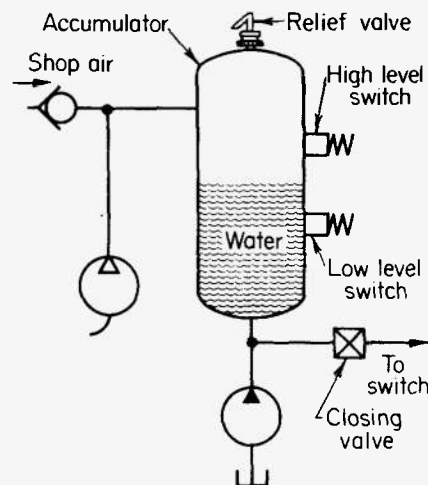


Fig. 2-39. Nonseparated Pneumatic-loaded Hydraulic Accumulator

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

(2) *Separated-type*: Aeration in the pneumatic-loaded accumulator can be eliminated by providing a barrier between the pressurizing gas and the hydraulic

fluid. Diaphragms, bladders, or pistons are used as barriers. A diaphragm-type accumulator is shown in Fig. 2-40. The spherical vessel is separated into two compartments by a flexible diaphragm. One compartment is connected to the hydraulic system and the other to the high-pressure gas system. In most designs a spring-loaded, normally-open check valve or a screen is provided at the liquid connection to prevent extrusion of the diaphragm into the liquid line when the fluid is discharged.

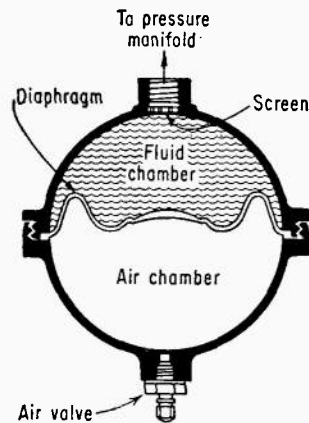


Fig. 2-40 . Diaphragm-type Pneumatic-loaded Hydraulic Accumulator

[From: E. Lewis, *Design of Hydraulic Control Systems*. Used by permission of McGraw-Hill, Inc.]

The bladder-type accumulator usually has a bladder inside a cylindrical shell with pressurized gas inside the bladder and the hydraulic fluid between the bladder and the housing (Fig. 2-41). The bladder is usually constructed with the thinnest wall near the gas port. It thus expands at the top first and then along the walls, forcing the liquid out through the poppet valve. This design can be used for ratios of maximum to minimum pressure up to about 5 to 1 and, because of the low inertia of the bladder, it is especially suitable for damping pulsations.

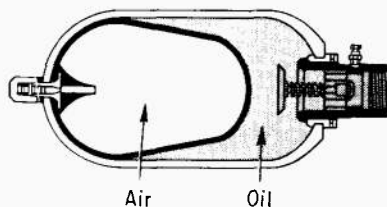


Fig. 2-41. Bladder-type Pneumatic-loaded Hydraulic Accumulator

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

A free-floating piston can also serve as a barrier between the gas and hydraulic fluid (Fig. 2-42). This type is less effective as a pulsation damper than is the bladder-type.

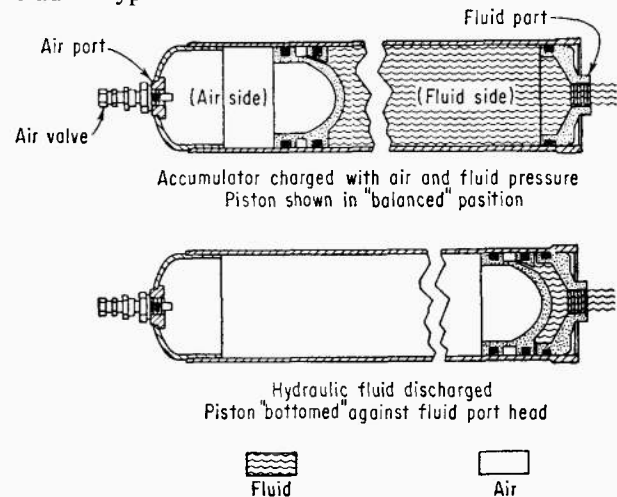


Fig. 2-42. Free-floating Piston, Pneumatic-loaded Hydraulic Accumulator

[From: E. Lewis, *Design of Hydraulic Control Systems*. Used by permission of McGraw-Hill, Inc.]

The separated, pneumatic-loaded accumulators are the most commonly used. They are small, lightweight, and can be mounted in any position.

2-7.2 ACCUMULATOR SELECTION CONSIDERATIONS

The factors which enter into the selection or specification of accumulators depend on the desired function of the unit in the hydraulic system. The compression and expansion of the gas in pneumatic-loaded accumulators are governed by the laws of gas dynamics. If discharge time is rapid (less than about 1 min for most applications), the expansion process can be assumed to be adiabatic. Isothermal relations can be used for compression if the process is slow.

The precharge pressure should be selected so that use is made of all liquid in the accumulator. The total volume required is the sum of the compressed gas volume and the volume of the liquid required by the system. The compressed gas volume is a function of the charge and discharge times. The required liquid volume must be determined from the desired performance of the accumulator. Empirical relations are available to determine the liquid volume required to effectively damp pump pressure surges or to suppress line

shock caused by sudden liquid deceleration. When used to decrease line shock, the accumulator should be located near the source of shock.

Accumulator systems, if they are used to store liquid energy, are often separated from the power source by a check valve. If the leakage is negligible, temperature fluctuations can induce gas-volume changes which, in turn, could generate harmful pressure variations in the system. If the hydraulic system must operate throughout a range of temperatures, it is necessary to conduct a P - V - T analysis of all locked accumulator circuits. The accumulator is precharged to a pressure P_g with gas which occupies the total accumulator volume. Then liquid at pressure P_f and temperature T_a is introduced into the accumulator, compressing the gas to a volume V_g' with a liquid-gas temperature of T_a' . Changing the liquid-gas temperature to T_a' does not result in a significant volume change but rather a change in accumulator pressure to P_g' . It is this pressure which could harm components or cause system malfunctions. Using the gas compressibility factor Z_g , defined as $Z_g = PV/NR^\circ R$, the pressures and temperatures at constant volume are related by

$$\frac{P_f}{Z_g T_a} = \frac{P_g'}{Z_g' T_a'} \quad (2-1)$$

Since both P_g' and Z_g' are unknown in this relation, a trial-and-error method, using appropriate values from compressibility charts, must be used to evaluate the pressure change which results from a specified temperature change.

2-8 VALVES

Valves are used in hydraulic circuits to control pressure, flow direction, or flow rate. They utilize mechanical motion to control the distribution of hydraulic energy within the system.

2-8.1 VALVE CONFIGURATIONS

A valve directs the distribution of hydraulic energy within a system by the operation of a mechanical element in the valve. There are three configurations or modes of operation—sliding, seating, and flow dividing.

2-8.1.1 Sliding-spool Valves

The sliding-spool valve is the most frequently used type in hydraulic systems. Fig. 2-43 illustrates the major configurations which employ the sliding spool. These are classified in terms of the type of center which exists when the spool is in the neutral position. Other factors used in spool-valve classification are the number of ways in which flow can traverse the valve and the number of lands on the spool.

2-8.1.2 Seating Valves

The two-jet flapper valve shown in Fig. 2-44 is an example of a seating valve. Such devices are frequently used as the first stage in a two-stage servovalve (see par. 2-8.3.6). They are limited to low-power applications because of their relatively high leakage rates. Tolerances are not as close on flapper valves as on spool valves and, hence, they are less expensive and less sensitive to fluid contamination.

Poppet valves (Fig. 2-45) also use the seating configuration. However, they are essentially two-way valves and, therefore, are limited to applications in which flow reversal is not required, e.g., relief valves and check valves.

2-8.1.3 Flow-dividing Valves

The jet-pipe valve, Fig. 2-46, utilizes the flow-dividing configuration. In the arrangement shown, flow is metered into two receivers by a nozzle. Equal areas of the two receivers are covered by the nozzle. The resulting forces provide hydraulic balance. The principal advantage of the jet-pipe valve is its ability to accommodate relatively high levels of fluid contamination. However, its characteristics are difficult to predict, and it exhibits slow response and large null flow. Like the flapper valve, the jet-pipe valve is more effective as a pilot stage than as a main second stage in servovalves. This is particularly the case if high pressure gain is required at high flow rates.

2-8.2 VALVE TYPES

Valves are classified according to their function in the hydraulic system. These basic types are pressure-control valves, directional-control valves, and volume-control valves. Most valves can be regarded as some combination of these basic types.

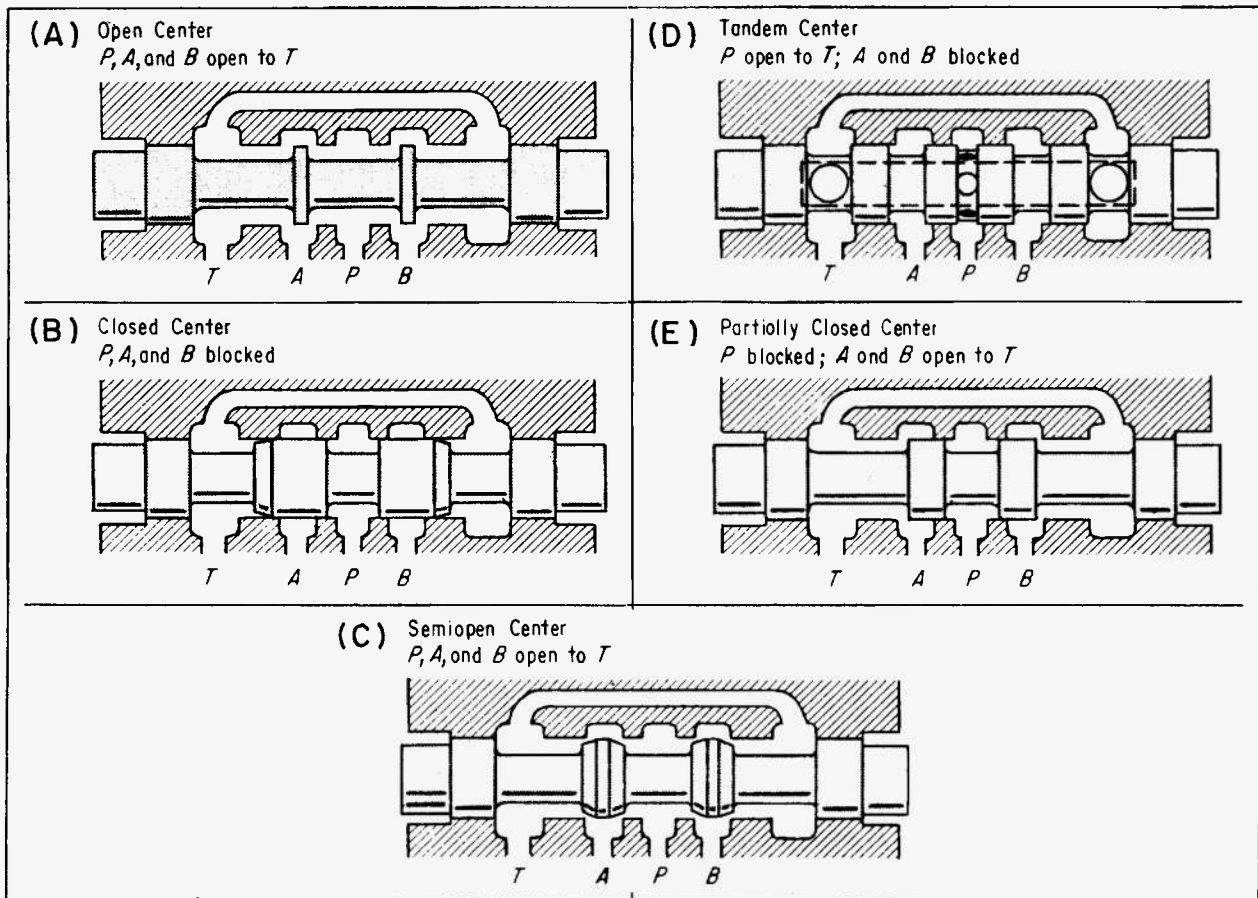


Fig. 2-43. Major Types of Sliding-spool Hydraulic Valve Configurations

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

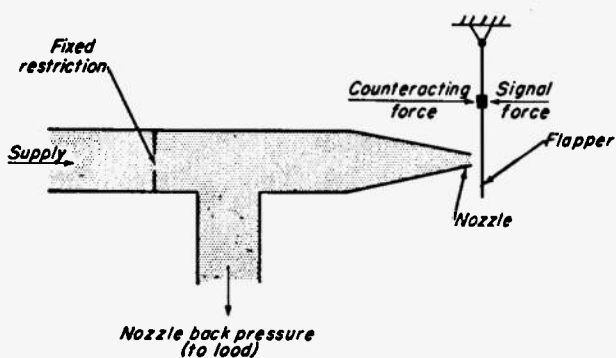


Fig. 2-44. Sketch of a Flapper Seating Valve

[From: *Fluid Power Handbook*. Used by permission of Industrial Publishing Co.]

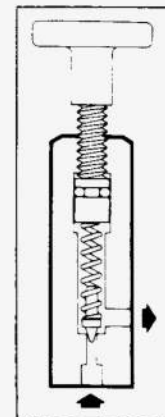


Fig. 2-45. Direct Spring-loaded Poppet-type Pressure Relief Valve

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

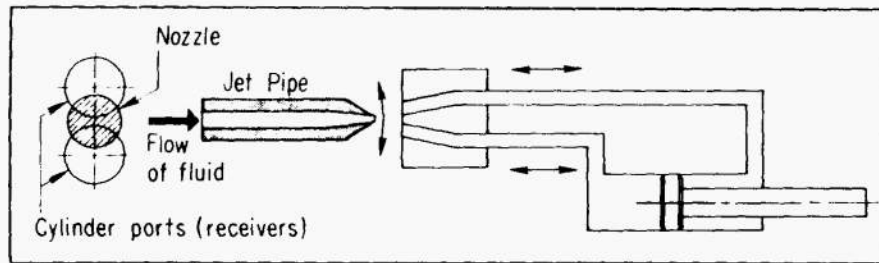


Fig. 2-46. Jet-pipe Flow-dividing Valve

[From: Fluid Power Issue, *Machine Design*. Used by permission of Penton Publishing Co.]

2-8.2.1 Pressure-control Valves

A pressure-control valve either limits the pressure in various circuit components or changes the direction of all or part of the flow when the pressure at a certain point reaches a specified level. Such controls are directly or indirectly actuated by some system-pressure level.

(1) *Relief valves*: A relief valve limits the maximum pressure that can be applied to the part of the system to which it is connected. It acts as an orifice between the pressurized region and a secondary region at a lower pressure. In most applications, the relief valve is closed until the pressure attains a specified value. Then the flow through the valve increases as the system pressure rises until the entire system flow is vented to the low-pressure region. As the system pressure decreases, the valve closes.

There are three types of relief valves—direct-acting, differential, and pilot. An adjustable spring load provides the pressure setting in all three types. In the direct-acting pressure-relief valve, the system pressure acts directly on the spring (Fig. 2-47). This type is usually used on low-pressure systems or when relief-valve conditions are expected only rarely. Valve chatter or pressure fluctuations are often a problem, which results from the fact that the springs required in such a valve are heavy. The differential relief valve shown in Fig. 2-48 can be constructed with a much lighter spring than the direct-acting type because the system pressure acts over only a differential area. In the pilot-operated relief valve, pressurized liquid is used to assist the spring (Fig. 2-49). The liquid passes from the supply line through a restricted passage to a control chamber where it acts on a plunger to add to the spring force. The force is limited by a small-capacity, direct-acting pilot relief valve. The pilot-operated relief valve is usually specified for systems which require frequent relieving.

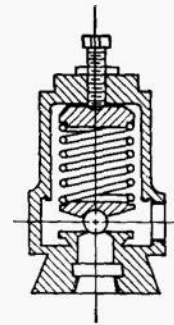


Fig. 2-47. Direct-acting Pressure-relief Valve

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹ Used by permission of McGraw-Hill, Inc.]

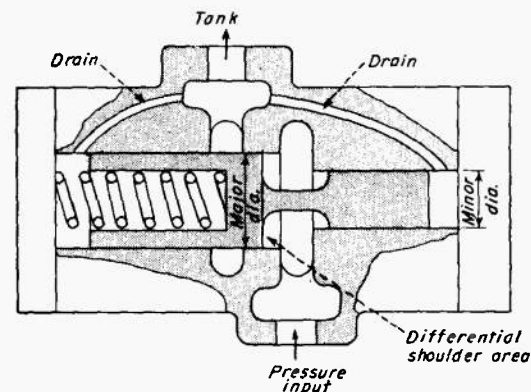


Fig. 2-48. Differential Pressure-relief Valve

[From: *Fluid Power Handbook*. Used by permission of Industrial Publishing Co.]

(2) *Unloading valves*: An unloading valve provides a vent to a low-pressure area when a specified pilot pressure is applied (Fig. 2-50). The signal is provided by an external source. These valves can be applied in

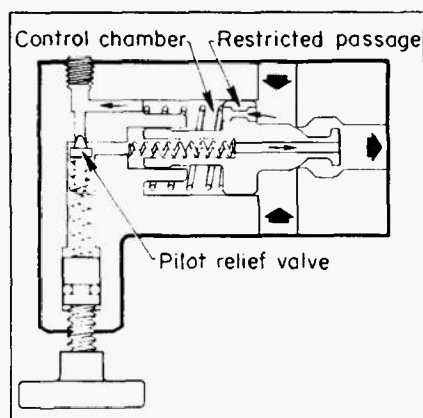


Fig. 2-49. Pilot-operated Pressure-relief Valve

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

circuits which allow a pump to build up to a specified pressure and then discharge to a reservoir at very low pressure. A typical application is in a double pump system where a high-volume, low-pressure pump is completely loaded at maximum pressure, while a low-volume, high-pressure pump continues to develop higher pressure.

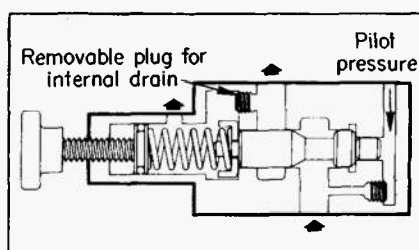


Fig. 2-50. Pilot-operated Unloading Valve

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

(3) *Load-dividing valves*: In a circuit with two pumps operating in series, the load can be equally divided between the pumps by a load-dividing valve (Fig. 2-51). The low-pressure pump discharge is connected to a larger piston area. The low-pressure flow tends to open the valve and relieve the pump discharge to the reservoir. The high-pressure pump discharge is connected to the small area and, assisted by the spring, tends to close the valve. The ratio of the pressure produced at the low-pressure pump to the discharge pressure of the high-pressure pump is the same as the valve-area ratio.

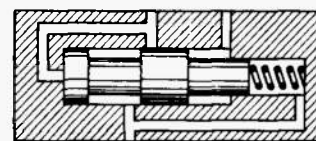


Fig. 2-51. Load-dividing Valve

[From: E. C. Fitch, *Fluid Power and Control Systems*¹. Used by permission of McGraw-Hill, Inc.]

(4) *Sequence valves*: The order of flow to different parts of a hydraulic system can be controlled by sequence valves. This is accomplished by controlling minimum pressure. Either an internal or external pilot pressure can be applied. Fig. 2-52 shows an externally-piloted, externally-drained sequence valve. The inlet pressure must reach a prescribed value before the flow is allowed to pass through the valve. In some designs the spring is assisted by a signal pressure applied at the drain.

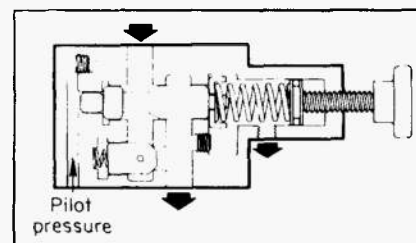


Fig. 2-52. Sequence Valve

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

(5) *Back-pressure valves*: The counterbalance back-pressure valve can be used to allow free flow in one direction but restricted flow in the opposite direction (Fig. 2-53). The pilot pressure can be external or internal. This valve can be used, for example, to prevent the

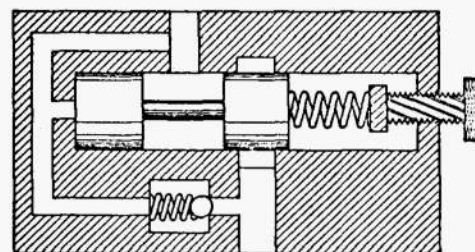


Fig. 2-53. Counterbalance Back-pressure Valve

[From: E. C. Fitch, *Fluid Power and Control Systems*¹. Used by permission of McGraw-Hill, Inc.]

weight of a vertically mounted piston from causing the piston to descend. The spring setting produces a back pressure on the piston which counterbalances the force of gravity.

(6) *Regulator valves:* The function of one type of pressure-regulator valve, or pressure-reducing valve, is to supply a prescribed reduced outlet pressure regardless of the pressure at the valve inlet. In this type, shown in Fig. 2-54, the outlet pressure is balanced against a spring. A drop in downstream pressure allows the spring to increase the valve opening and increase the downstream pressure. In the second type of regulator valve, the inlet pressure is balanced against both the spring and the outlet pressure (Fig. 2-55). The spring setting then determines the amount of pressure reduction across the valve. Hence, this type is used to maintain a fixed pressure differential across the valve for all values of upstream pressure.

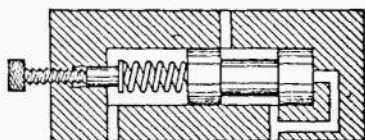


Fig. 2-54. Pressure Reducing Valve (Constant Downstream Pressure)

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹ Used by permission of McGraw-Hill, Inc.]

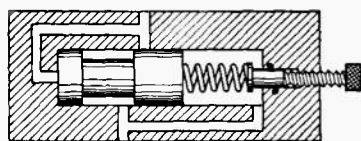


Fig. 2-55. Pressure Regulating Valve (Constant Pressure Differential)

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹ Used by permission of McGraw-Hill, Inc.]

(7) *Pressure switch:* When a pressure-actuated electric signal is required for system control, a pressure switch is used (Fig. 2-56). The system pressure acts against an adjustable spring used to preset the switch. When the pressure reaches the specified value, the microswitch is actuated. The signal can be used to actuate a variety of control elements. Although the pressure switch is not a valve, it is a valuable control element in valving systems.

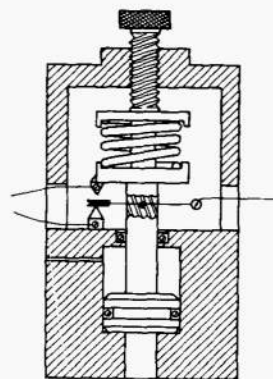


Fig. 2-56. Pressure Switch

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹ Used by permission of McGraw-Hill, Inc.]

(8) *Hydraulic fuzes:* A hydraulic fuze employs a frangible diaphragm or similar device which fractures at a preset pressure. It can thus be used as a substitute for, or in conjunction with, a pressure control valve. Hydraulic fuzes can be used with safety valves to prevent hydraulic fluid loss under normal operating conditions. They usually do not have automatic reset capabilities. It is necessary to manually replace the diaphragm if the hydraulic fuze is actuated.

2-8.2.2 Directional-control Valves

Controlling where and when the hydraulic fluid is delivered to various parts of the system is the function of directional-control valves. These valves are used to control the operation of actuators.

(1) *Check valves:* The simple check valve permits free flow in one direction and blocks flow in the reverse direction (Fig. 2-57). When flow is in the normal direction, the liquid pressure acts against the spring tension to hold the poppet off the seat. When flow stops, the spring seats the poppet and liquid cannot pass in the reverse direction. Check valves can also be pilot-operated (Fig. 2-58). In such a unit, flow can proceed freely in one direction, but reversed flow depends upon the pilot actuation. Pilot-operated check valves can be either normally closed or normally open.

(2) *Position valves:* The function of the position valve is to control the introduction of liquid to the lines of the system. When the valve is operated, the liquid lines within it are shifted. Position valves are classified in terms of the number of valve positions and the number of liquid ports, e.g., a four-way, three-position valve.

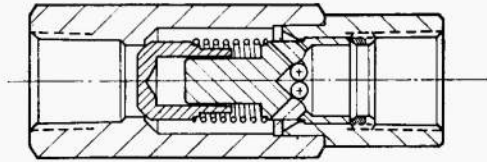


Fig. 2-57. Poppet-type Check Valve

[From: E. C. Fitch, *Fluid Power and Control Systems*¹. Used by permission of McGraw-Hill, Inc.]

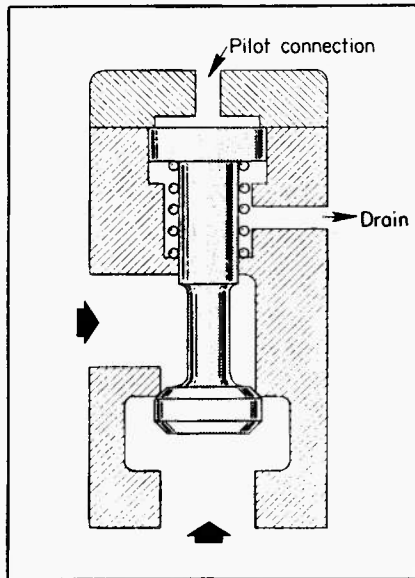


Fig. 2-58. Pilot-operated Check Valve

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

Two-way valves are generally shut-off valves. There are several types—spool, poppet, plug, ball, and rotary. Unlike a check valve, the two-way valve can block flow in both directions.

Three-way and four-way valves are available with either two or three positions and with open or closed centers. There are six basic types—spool, poppet, packed plunger, plug, plate, and rotary. A three-way valve can be used, for example, to control a single-acting linear actuator. One of the many applications of a four-way valve is control of double-acting actuators. Special valves are available in five- and six-way versions.

Several spool-valve configurations are shown in Fig. 2-43. The function and application of a specific valve are determined by the spool configuration and the method of actuation. For example, a three-position valve can be used to isolate an actuator from the circuit,

to provide a bypass to the reservoir around the actuator, or to hold an actuator in an intermediate position. The open-center configuration, when centered, permits the liquid to flow back to the reservoir with little pressure drop. In the closed-center configuration, the ports are blocked when the valve is centered. The same source can then be used for other valves in parallel. When the tandem-center configuration is centered, the downstream ports are blocked; but liquid can freely flow to the reservoir and, hence, the pump does not necessarily have to operate at maximum pressure. The partially-closed center is commonly used as a pilot spool to actuate a primary spool. The inlet is closed but the system ports are open to the reservoir. In the semi-open configuration, the cylinder ports are open to the high-pressure port. This type permits relief of high pressure at the cylinder ports caused by a temporary overload force on the actuator.

Many of the position-valve designs incorporate other functions in addition to flow-direction control. One such example is the deceleration valve illustrated in Fig. 2-59. The flow can be shut off at a rate determined by the taper of the spool. Several deceleration valve designs are available, and some are provided with adjustable spool tapers.

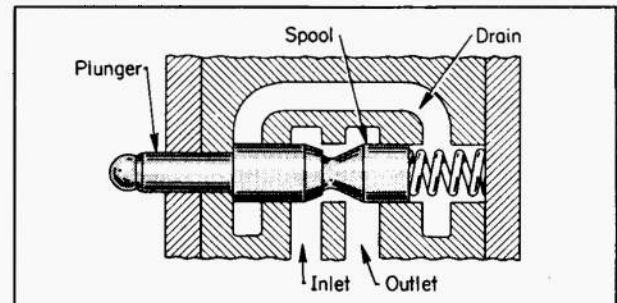


Fig. 2-59. Mechanically Operated, Nonadjustable Deceleration Valve

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

Shuttle valves are used when control is required from more than one source. Fig. 2-60 shows a three-port shuttle valve which provides a liquid path for two alternate sources. As long as pressure in the right inlet port is greater than in the left, the shuttle piston closes the left port. When pressure at the left port becomes greater than at the right, the piston moves to the right against a stop, closing the right port and opening the left.

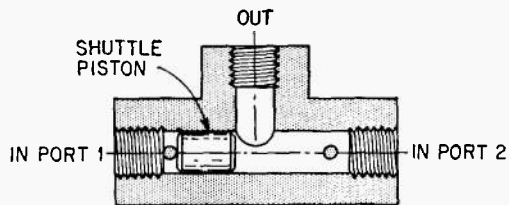


Fig. 2-60. Three-port Shuttle Valve

[From: Pippenger and Hicks, *Industrial Hydraulics*².
Used by permission of McGraw-Hill, Inc.]

A time-delay valve is shown in Fig. 2-61. The valve permits the liquid to flow freely in one direction. If the flow is reversed, liquid is trapped behind the spool and allowed to escape to the reservoir through an orifice. The valve does not open until the blocking liquid escapes, thus providing a time delay in the flow reversal.

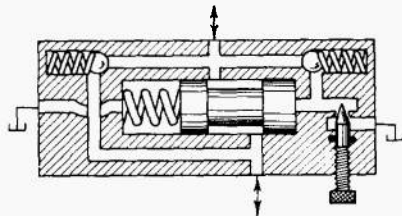


Fig. 2-61. Time-delay Valve

[From: E. C. Fitch, *Fluid Power and Control Systems*¹.
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2-8.2.3 Volume-control Valves

Volume-control valves are used to regulate the rate of liquid flow to different parts of a hydraulic system. Control of flow rate is a means by which the speed of hydraulic machine elements is governed. The rate of flow to a particular system component is varied by throttling or by diverting the flow.

(1) *Globe and needle valves:* Flow rate is changed in a globe valve by means of a disk, plug, or ball which nests against a seat (Fig. 2-62). The needle valve uses a tapered stem which nests against a seat and, in so doing, gradually reduces the flow area (Fig. 2-63). Needle valves have a smaller flow area and higher pressure drop than the globe valve, but are more suitable in throttling the flow. The globe valve is used to throttle only in lines where the liquid velocity is relatively low. Changes in the pressure drop across globe or needle valves produce variations in the flow rate, i.e., they are not pressure-compensated. This shortcoming limits their utility in applications where precise flow-rate control is required.

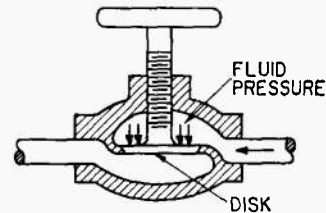


Fig. 2-62. Disk-type Globe Valve

[From: Pippenger and Hicks, *Industrial Hydraulics*².
Used by permission of McGraw-Hill, Inc.]

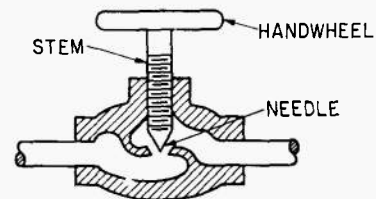


Fig. 2-63. Needle Valve

[From: Pippenger and Hicks, *Industrial Hydraulics*².
Used by permission of McGraw-Hill, Inc.]

(2) *Pressure-compensated flow-control valves:* A constant pressure drop across the valve orifice is required to assure accurate flow control. This is accomplished with the pressure-compensated flow-control valve. In such valves the pressure drop across the metering orifice is used to assist a spring in moving a balanced spool (Fig. 2-64). A change in pressure drop produces a rapid compensation in the form of spool motion. This spool adjustment causes the pressure drop to return quickly to its original value, thus maintaining constant flow. The orifice pressure drop, determined by spring force and spool area, is relatively low.

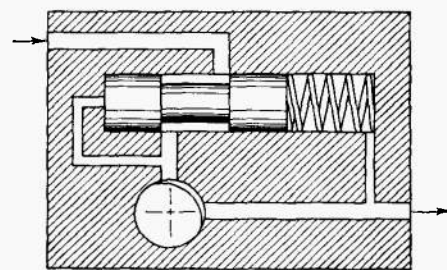


Fig. 2-64. Pressure-compensated Flow-control Valve

[From: E. C. Fitch, *Fluid Power and Control Systems*¹.
Used by permission of McGraw-Hill, Inc.]

(3) *Positive-displacement metering valves:* An intermittent flow of a specific volume of liquid can be obtained by using a positive-displacement metering valve. The valve consists of a free-floating piston whose stroke can be changed by an adjustment screw (Fig. 2-65). Such valves can be applied, for example, to control flow to a linear actuator used to obtain accurate, intermittent motion.

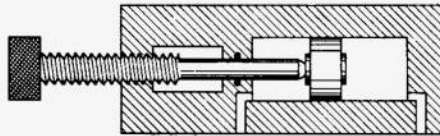


Fig. 2-65. Positive-displacement Metering Valve

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹ Used by permission of McGraw-Hill, Inc.]

(4) *Flow-divider valves:* Flow-divider valves utilize sliding elements to change the orifice area (Fig. 2-66). They distribute the flow to multiple lines, each of which then has the same flow rate downstream of the valve. They are generally pressure-compensating valves and are frequently used to synchronize the motion of several linear actuators.

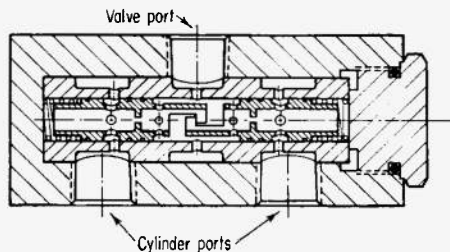


Fig. 2-66. Pressure-compensated Flow-divider

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹ Used by permission of McGraw-Hill, Inc.]

2-8.3 VALVE ACTUATION

In order to respond to the system requirements or to the commands of the operator, hydraulic control valves must be provided with a means of actuation. Some form of actuation is required, for example, to move the spool in a position valve, to adjust flow-control valves, or to change the setting of a pressure-control valve. The actuation methods normally used are manual, mechanical, electrical, or fluid. Mechanical actuators include springs, cams, and mechanical linkages. Electric control utilizes solenoids. Fluid actuation requires either a liquid or gas pilot fluid.

2-8.3.1 Manual Actuation

Manual actuation requires action by an operator who must make a control judgment based upon some system requirement. Manual valve response is limited by the action of the operator; hence, flow reactions, such as forces generated in the system, are more critical than in pilot- or electrically-actuated valves. Manual control is frequently used when response time is not critical and when some system change must be initiated by the operator. It is widely used in machine tools and mobile equipment.

2-8.3.2 Spring Actuation

From the discussion of valves in this chapter, it is evident that springs are widely used to provide force for a variety of valve operations. However, they seldom supply the entire force required; they are usually assisted by a force from another source which actually determines the manner in which the valve mechanism will react. Often the primary valve actuator acts against a spring which tends to hold the valve in the neutral position.

2-8.3.3 Cam Actuation

In a cam-actuated valve, the operating linkage is actuated by a cam which is mounted on a moving machine element. The deceleration valve illustrated in Fig. 2-59 is equipped to be operated by a cam.

2-8.3.4 Solenoid Actuation

Solenoid-operated valves are generally small, single-stage devices. They can, however, be used to control large, pilot-operated valves as part of a two-stage system. In such systems, current requirements are low, thus reducing the size of the solenoids. Most applications use 115 V, 60 cps solenoids; however, they are available in a wide range of AC or DC voltages. DC solenoids are quiet in operation, whereas AC solenoids may hum or chatter. The solenoids are energized by signals from pressure switches, limit switches, or timers which usually operate through power or signal relays to accommodate the current required to actuate the solenoid.

Solenoid actuation affords considerable flexibility in hydraulic system design. System commands can be obtained from signals in any part of the circuit. For example,

flow conditions can be controlled by pressure levels through the use of pressure switches, or machine motion can be controlled by limit switches. Time delays can be obtained by using a pressure or limit switch to activate a timer. System operational sequences can be programmed on cards or tape to provide automatic control.

2-8.3.5 Pilot Fluid Actuation

Air or oil can be used to provide fluid power for the actuation of valves. Air can be used to activate single-stage valves, or pilot valves on multi-stage units. Large flow rates can be controlled with air-actuated, pilot-operated, two-stage valves which require relatively low-pressure signals.

One advantage of pilot-fluid actuation is the long life of fluid components compared to that of electric components. This factor is particularly important in machines which must operate through many cycles in a relatively short period, as is the case with many production manufacturing machines.

2-8.3.6 Servomechanism Actuation

Valves actuated by servomechanisms, called servovalves, use an electric signal to control the hydraulic output. The electric signal actuates a servomechanism—for example, a torque motor—which actuates the valve. Most servovalves are two-stage with the servo driving the pilot stage. Fig. 2-67 shows a two-stage, spool-type servovalve in which the torque motor actuates the pilot spool which, in turn, directs liquid to the main stage. Single stage valves are practical only for limited flows.

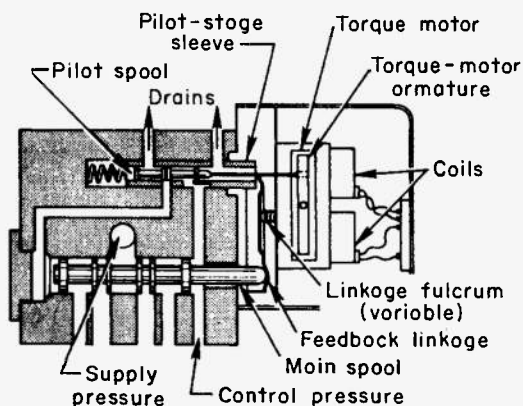


Fig. 2-67. Two-stage Spool-type Servovalve

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

The pilot stage of a two-stage servovalve consists of an electromechanical transducer and a hydraulic amplifier. The transducer converts the electrical signal into mechanical motion which is then converted into hydraulic output by the amplifier. The transducers most frequently used are the torque motor and the moving coil (Fig. 2-68). A polarized torque motor consists of an armature of a magnetic material which turns in a permanent magnetic field. The armature motion depends on the strength and polarity of the current. The moving coil consists of a coil suspended in the gap of a magnet. Displacement is proportional to the current.

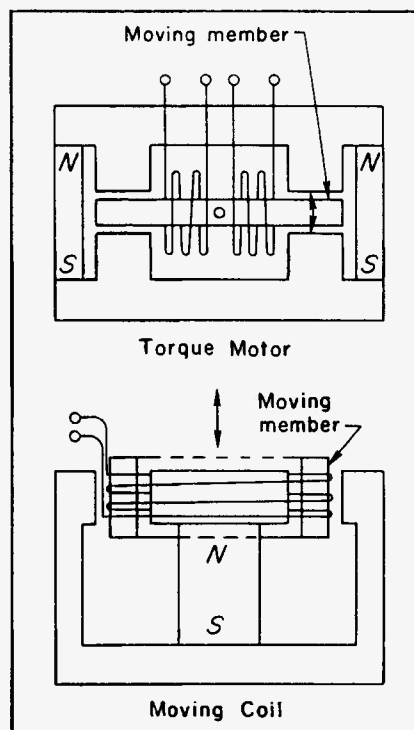


Fig. 2-68. Servovalve Transducers

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

Servovalves commonly employ feedback systems whereby the position of the main spool is signaled to the pilot stage which then makes any necessary correction. Typical systems for feedback from the main stage to the pilot stage are illustrated in Fig. 2-69.

2-8.4 PRINCIPLES OF VALVE ANALYSIS

Knowledge of the performance capabilities of hydraulic valves is essential in the design and fabrication

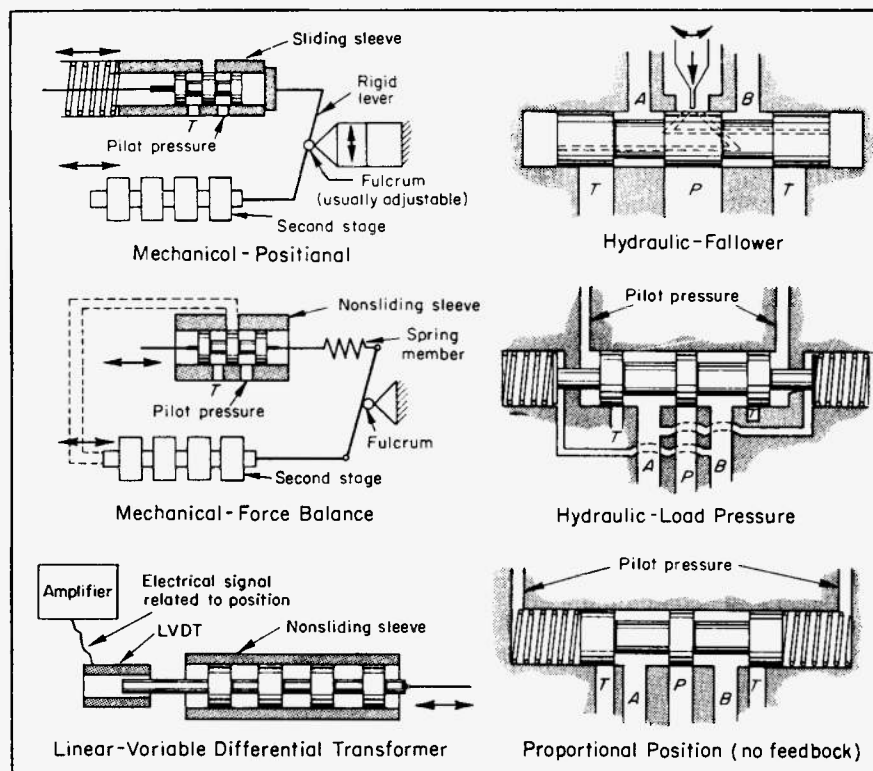


Fig. 2-69. Servovalve Internal Feedback Systems

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

of a hydraulic system. Prediction of valve performance requires curves of pressure vs flow and evaluation of several valve coefficients. Pressure-flow curves can be generated from experimental data, and valve coefficients can be derived from these curves. However, an analytical approach to determine valve coefficients is possible. The difficulty of the analysis depends on the complexity of the valve. In addition to pressure-flow curves and valve coefficients, valve analysis can yield general flow equations, leakage flow information, and expressions for the forces that occur in valves.

A complete analytical method for the analysis of valves is presented in the text by Merrit (Ref. 4). The method given by Merrit (Ref. 4) is for four-way spool valves with examples of the applications of the method to other types of valves.

A complete analysis of a valve will yield the following information:

(1) *General Flow Relationships*: General flow equations express the flow of hydraulic fluid at the load or at the pump as a function of the hydraulic system and valve parameters.

(2) *Valve Coefficients*: Valve coefficients are an expression of the sensitivity of the flow of hydraulic fluid at the load to changes in the valve opening or the liquid pressure.

(3) *Leakage Flows*: In practice, all valves have clearances between moving parts and these clearances result in leaks. Leakage flow equations relate the magnitude of the leakage to valve and system parameters.

(4) *Stroking Forces*: Stroking forces are the forces that oppose the motion of the valve spool or stem. They affect the ease of operation of a valve.

(5) *Flow Forces*: Flow forces are forces on, or in, the valve due to hydraulic reactions.

2-8.5 VALVE DESIGN CONSIDERATIONS

The first consideration in valve design for a specific application is the type of valve to be used. The three major types—sliding, seating, and flow-dividing valves—are illustrated by the spool valve (Fig. 2-43), the flapper valve (Fig. 2-44), and the jet-pipe valve (Fig. 2-46),

respectively. Jet-pipe and flapper valves are not as widely used as spool valves; so descriptions of their design considerations will be limited to their general characteristics.

The jet-pipe valve is the least used of the three valves mentioned. It is characterized by a large null flow and slow response. Its performance parameters are not easily predicted. Its chief advantage is its insensitivity to dirty fluids. The jet-pipe valve is a common form of preamplifier but is usually limited to low-pressure application because of possible atomization of the fluid at high pressures. It was developed by Askania in Sweden and is often referred to as the Askania nozzle.

Flapper valves, unlike jet-pipe valves, offer linear pressure-flow curves and predictable performance characteristics. Other advantages of flapper-type valves are their insensitivity to dirt and relative low cost due to loose tolerances in their manufacture. Flapper-type valves are often used as preamplifiers but are seldom used alone for high power applications; they are suitable for low-power applications where leakage due to their relatively loose tolerances is not a major concern. In applications where leakage must be kept to a minimum, however, spool valves are recommended.

Important spool valve design considerations are tolerances, choice of three- or four-way valves, number of lands, shape of ports, type of valve center, valve area gradient, length of valve stroke, and maximum valve area.

All dimensions of spool valves, especially radial dimensions between the spool and sleeve, should have tolerances of ± 0.0001 in. or less if high performance is expected. In some cases, however, valve tolerances may be as high as ± 0.0003 in. The importance of valve tolerances is reflected in their effect on flow gain and pressure sensitivity near the null condition. Flow gain and pressure sensitivity express the hydraulic fluid flow and pressure, respectively, at the load as a function of valve spool position. Since more than one orifice may be open as the spool approaches the null position, the flow gain and pressure sensitivity may become nonlinear (see Fig. 2-70).

In choosing between three- and four-way valves, the economic advantage favors three-way valves since they require only one actuator line and have only three critical dimensions. Four-way valves, however, offer twice the pressure sensitivity of three-way valves.

In choosing among two-, three-, and four-land spools for use in four-way valves, the many drawbacks of two-land spools should be weighed against their easier and cheaper construction as compared to three- and four-land spools. The two major disadvantages of the

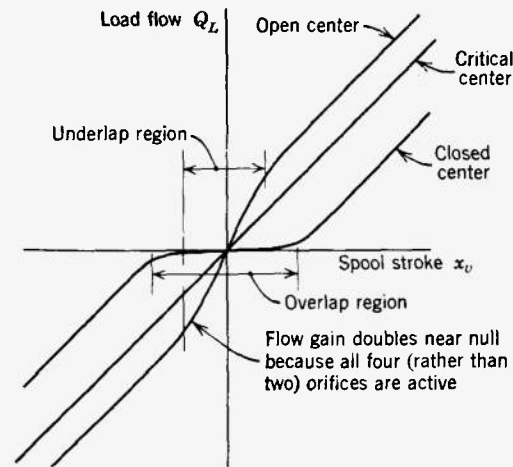


Fig. 2-70. Flow Gain of a Spool Valve

two-land spool are that it is statically unbalanced and that the valve lands may lodge in the sleeve openings if the ports constitute a major portion of the periphery of the spool. Three- and four-land spools avoid both of these disadvantages and therefore are more commonly used.

The type of flow gain characteristics desired from a valve determines the choice of port shape. Rounded ports produce nonlinear flow gain characteristics, whereas linear flow gain characteristics result from rectangular-shaped ports. In most high performance systems, rectangular ports are essential. Furthermore, rectangular ports offer good servo performance over a broad operating range.

The choice among open center, closed center, and critical center valves is based on several design considerations. Open center valves are generally used where constant system flow is desired; when the valve must be left in the null position for long periods of time; and when continuous flow is required to maintain reasonable fluid temperatures. Open center valves have the disadvantage of being unstable at null. To allow for this, the valve must be adjusted to a lower flow gain when it is away from the null position. Open center valves also exhibit power loss at null due to center flow.

Closed center valves are generally considered the least desirable of the three types because of their low gain characteristics at null. The result is a lack of control of the valve in the null region and a tendency for the output device to wander in position.

Critical center four-way spool valves are most frequently used and their chief design parameters are the valve area and the stroke. Maximum valve area or maximum orifice area is desirable since it favorably

affects null flow gain and adds system stability. Maximizing valve stroke is also desirable because with longer strokes, there is more resolution near null and improved performance with dirty fluids. With a long stroke, ports remain open longer and dirt particles are flushed from the orifice.

2-9 HEAT EXCHANGERS

Heat is generated in all hydraulic systems. The inherent mechanical and thermodynamic inefficiencies of pumps and motors result in heat generation. Much of this heat is transferred to the hydraulic fluid, causing a rise in fluid temperature. Since all hydraulic fluids exhibit a limited temperature range over which the viscosity and lubricating characteristics are optimum, the heat must be dissipated to assure satisfactory operation. Some heat is removed by dissipation to the environment. If this heat transfer is not sufficient to maintain the desired fluid temperature, it then becomes necessary to provide heat exchangers to supplement the natural dissipation.

The analysis of temperature-control problems in a hydraulic system begins with an estimate of the total heat rejection from the system. This can be done in several ways. The heat rejection can be treated as the input power less the actual mechanical work, based on a convenient time interval. It can also be estimated on the basis of pump output. The increase in thermal energy due to pump operation can be estimated by the relation (Ref. 1)

$$Q_p = 1.486 GP \left(\frac{1}{\eta} - 1 \right), \text{Btu/hr} \quad (2-2)$$

where

$$\begin{aligned} Q_p &= \text{increase in thermal energy due to pump, Btu/hr} \\ G &= \text{flow rate, gpm} \\ P &= \text{operating pressure, psi} \\ \eta &= \text{decimal operating efficiency} \end{aligned}$$

If the pump contributes to no external work, the power input goes entirely into increased thermal energy Q_p . Then (Ref. 1):

$$Q_p = 1.486 \frac{GP}{\eta}, \text{Btu/hr} \quad (2-3)$$

As a liquid flows through a flow control valve, the change in potential energy is dissipated as heat. This increase in thermal energy Q_ℓ is given as (Ref. 1):

$$Q_\ell = 1.486 G \Delta P, \text{Btu/hr} \quad (2-4)$$

where ΔP is the pressure drop in psi across the valve. A similar expression holds for the heat dissipated as liquid flows through a transfer line. The pressure drop is then the pressure drop through the line. With this simplified approach, the total thermal energy absorbed by the fluid is the sum of the pump contribution and that of all pressure drops. The heat can be dissipated from the surfaces of the circuit components and, if necessary, removed by a heat exchanger.

2-9.1 MODES OF HEAT TRANSFER

Heat can be removed from the system by all three of the basic modes of heat transfer—conduction, convection, and radiation.

2-9.1.1 Conduction

Thermal conduction is the transfer of heat through a gas, liquid, or solid by means of collisions or intimate contact between the molecules. The amount of heat transferred by conduction is given by Fourier's Law. For simple one-dimensional flow this law reduces to

$$Q = kA \left(\frac{\Delta T}{\ell} \right), \text{Btu/hr} \quad (2-5)$$

where

$$\begin{aligned} Q &= \text{rate of heat flow, Btu/hr} \\ k &= \text{thermal conductivity of material, Btu/(hr)(ft}^2\text{)(}^\circ\text{F/ft)} \\ A &= \text{area normal to direction of flow, ft}^2 \\ \Delta T &= \text{temperature difference between warmer and cooler surfaces of the material, } ^\circ\text{F} \\ \ell &= \text{thickness of material, ft} \end{aligned}$$

More general forms of the conduction equation must be used if the heat flow is other than one-dimensional.

2-9.1.2 Convection

Heat transfer by convection requires gross motion of liquid particles involving the transport of regions of the

liquid at different temperatures. Free, or natural, convection occurs when the liquid particles move because of density gradients established by temperature gradients. If the liquid is circulated by external means, the process is called forced convection. Convection heat transfer rate Q is governed by a relation developed by Newton (Ref. 1):

$$Q = hA\Delta T, \text{ Btu/hr} \quad (2-6)$$

where

- Q = rate of heat flow, Btu/hr
- h = convective film coefficient, Btu/(hr)(ft²)(°F)
- A = area of surface exposed to the fluid and normal to heat flow direction, ft²
- ΔT = temperature difference between the fluid and the surface, °F

This relation actually defines the film coefficient h . Only in the most ideal situations can the film coefficient be computed. Empirical relations are often employed to estimate a value of h .

2-9.1.3 Radiation

Thermal radiation involves the transport of thermal energy by means of electromagnetic radiation. The amount of heat transferred by radiation depends on the relative configuration of the areas which exchange heat, their temperatures, and the nature of their surfaces. The governing relation is

$$Q = FA\sigma(T_2^4 - T_1^4), \text{ Btu/hr} \quad (2-7)$$

where

- Q = rate of heat flow, Btu/hr
- F = a dimensionless factor which accounts for the geometric orientation of the surfaces and their emittances
- A = area of radiating surface, ft²
- σ = Stefan-Boltzmann constant = 0.1714×10^{-8} Btu/(hr) (ft²) (°R⁴)
- T_2 = temperature of radiating surface, °R
- T_1 = temperature of sink or receiving surface, °R

2-9.1.4 Overall Heat Transfer Coefficient

The contributions of conduction, convection, and radiation to net heat transfer can be combined by making use of the concept of the overall heat transfer coefficient which is defined by the relation

$$Q = UA\Delta T_{total} \quad (2-8)$$

where

- Q = rate of heat flow, Btu/hr
- U = overall heat transfer coefficient, Btu/(hr)(ft²)(°F)
- A = heat transfer area, ft²
- ΔT_{total} = total temperature difference across which the heat is being transferred, °F

The overall coefficient is a measure of the thermal conductance of the system,

$$UA = \frac{1}{R_1 + R_2 + \dots + R_n} \quad (2-9)$$

where R_i is the thermal resistance of system component i and has units of hr·°F/Btu.

Consider, for example, the case of a counterflow plane wall heat exchanger as shown in Fig. 2-71. Under steady-state conditions the amount of heat transfer between the two fluids is given by

$$Q = h_{12}A(T_1 - T_2) = k_w \frac{A(T_2 - T_3)}{\ell_{23}} = h_{34}A(T_3 - T_4)$$

This can be expressed as three simultaneous equations for the temperature differences and solved for the total temperature difference:

$$\Delta T_{total} = T_1 - T_4 = \frac{Q}{A} \left(\frac{1}{h_{12}} + \frac{\ell_{23}}{k_w} + \frac{1}{h_{34}} \right) \quad (2-10)$$

or

$$Q = \frac{A\Delta T_{total}}{1/h_{12} + \ell_{23}/k_w + 1/h_{34}} \quad (2-11)$$

Then from Eq. 2-8

$$U = \frac{1}{1/h_{12} + \ell_{23}/k_w + 1/h_{34}} \quad (2-12)$$

Additional factors such as dirt and scale deposits can contribute to the thermal resistance in heat exchangers. In such cases, appropriate terms are added to the system resistances in Eq. 2-9.

2-9.2 TYPES OF COOLING SYSTEMS

In general, heat transfer in a hydraulic system will involve some combination of the three modes of heat

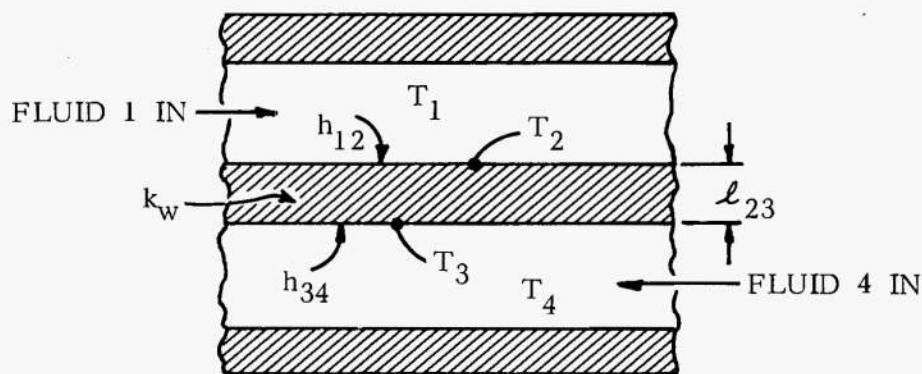


Fig. 2-71. Counterflow Plane Wall Heat Exchanger

transfer. If it is found that the heat dissipated from the surfaces of the system is insufficient to maintain a satisfactory fluid temperature, then a heat exchanger is required. Most heat exchangers for hydraulic fluids are either air-cooled or water-cooled.

2-9.2.1 Air-cooled Heat Exchangers

Air is often used as the coolant in heat exchangers for mobile hydraulic systems, or in stationary systems which generate moderate amounts of heat. A blower or fan is usually used to circulate the air across finned tubes through which the hydraulic fluid flows (Fig. 2-72). Air-cooled units are limited to applications where the desired hydraulic fluid outlet temperature is at least 10°F above the dry bulb air temperature.

2-9.2.2 Water-cooled Heat Exchangers

The use of water as a coolant is common practice in stationary systems. The film coefficient on the water side is generally the same order of magnitude as on the hydraulic-fluid side. Therefore, water-cooled heat exchangers are usually shell-and-tube type where the heat-transfer area on the cold side is approximately the same as on the hot side. Such an exchanger is shown in Fig. 2-73. It consists of a tube bundle within a shell. The tubes are baffled (not shown) so that the coolant flow in the shell is perpendicular to the tube axis. Most shell-and-tube heat exchangers used in hydraulic systems are either single- or double-pass units. In a single-pass unit, the two liquids generally flow in opposite directions. In a double-pass exchanger, the hydraulic fluid generally enters the same end at which the water enters and leaves.

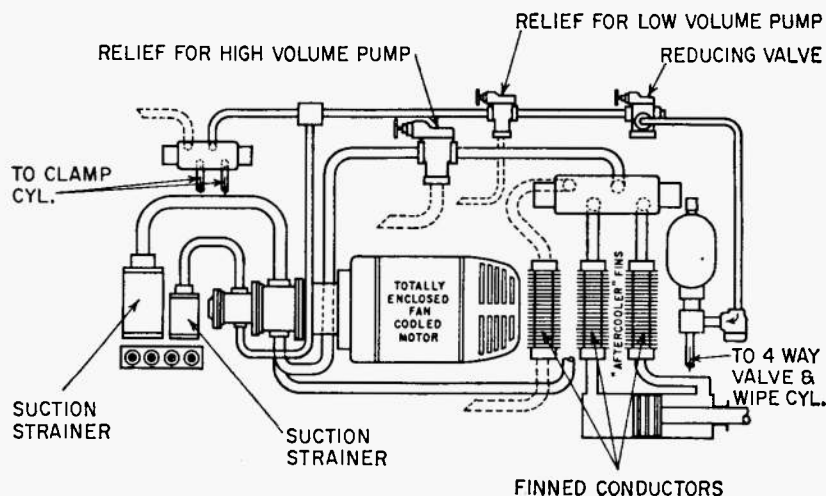


Fig. 2-72. Hydraulic Circuit With Air-cooled Heat Exchangers

[From: Pippenger and Hicks, *Industrial Hydraulics*². Used by permission of McGraw-Hill, Inc.]

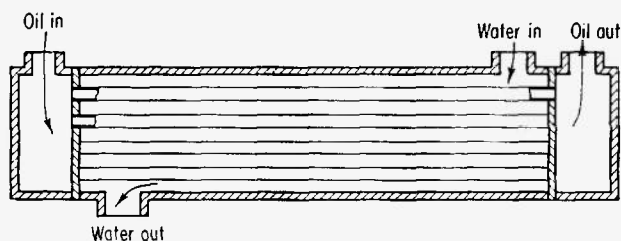


Fig. 2-73. Shell and Tube Single-pass Heat Exchanger

[From: E. C. Fitch, *Fluid Power and Control Systems*.¹
Used by permission of McGraw-Hill, Inc.]

Water-cooled, shell-and-tube heat exchangers are compact and low in initial cost. They can be used to obtain lower hydraulic-fluid temperatures than the air-cooled exchangers. Limitations include the possibility of corrosion and the cost of a continuous water supply. Copper alloys are used in standard heat exchangers, and special corrosion-resistant alloys are available. Removable tube bundles facilitate cleaning.

2-10 HYDRAULIC PIPING

The design of the liquid conductors is just as important as the design of other components of a hydraulic system. The hydraulic piping serves to contain and conduct the hydraulic fluid from one part of the system to another. Inadequate attention to piping design can lead to poor system operating characteristics and low efficiency.

Hydraulic piping systems are usually constructed from three types of fluid conductors—pipe, tubing, and flexible hose. Hose is used to accommodate relative movement between components. Most of the stationary piping, however, is either tubing or pipe. The advantages of tubing include better appearance, greater flexibility, better reusability, fewer fittings, and less leakage. The principal advantage of pipe is its relatively low cost.

2-10.1 HYDRAULIC LINE SIZE

The sizing of liquid conductors for hydraulic piping depends on considerations of mechanical strength, volume flow rates, pressure drop, pressure surges, and compression time.

2-10.1.1 Pressure Drop

The efficiency of a hydraulic line is determined by the pressure loss which should be as small as possible. The pressure required at the inlet is equal to the sum of the required outlet pressure and the pressure drop in the line. Hence, minimum pressure drop means minimum pumping requirements.

One convenient method for determining pressure drop in the distribution system—including piping, valves, headers, etc.—is to convert all flow passages to equivalent lengths of the same size liquid conductor. The length of a line of one diameter can be converted to the equivalent length of a given diameter line by the relation (Ref. 1)

$$L_e = L \left(\frac{D_e}{D} \right)^5, \text{ ft} \quad (2-13)$$

where

L_e = equivalent length of line, ft

L = length of line, ft

D_e = inside diameter of equivalent line, in.

D = inside diameter of line, in.

Flow passages such as valves, tees, elbows, etc., can be converted to equivalent lengths with (Ref. 1)

$$L_e = \frac{KD_e}{12f}, \text{ ft} \quad (2-14)$$

where

K = loss coefficient

f = coefficient of friction of liquid in the fitting

Values of the loss coefficient for several flow elements are given in Table 2-1. For some components, such as sequence valves, the loss coefficients change as the flow conditions vary.

When the components of the liquid distribution system have been converted to equivalent lengths of a common size, the pressure drop can be estimated from either of the two following expressions (Ref. 1)

$$\Delta P = 0.01345 f_s G^2 \left(\frac{L}{D^5} \right), \text{ psi} \quad (2-15)$$

$$\Delta P = 0.0808 f_s U^2 \left(\frac{L}{D} \right), \text{ psi} \quad (2-16)$$

where

ΔP = pressure drop, psi

L = line length, ft

D = inside line diameter, in.

U = liquid velocity, fps

TABLE 2-1.
LOSS COEFFICIENTS OF HYDRAULIC SYSTEMS¹

Flow Line Element	Loss Coefficient, K
Globe valve, wide open	10.0
Angle valve, wide open	5.0
Gate valve, wide open	0.19
1/4 closed	1.15
1/2 closed	5.6
3/4 closed	24.0
Standard T	1.8
Standard elbow	0.9
Medium-sweep elbow	0.75
Long-sweep elbow	0.60
45-degree elbow	0.42
Close return bend	2.2
Borda entrance	0.83
Sudden enlargement:†	
To reservoir or to large cylinder	1.0
$d/D = 1/4$	0.92
$d/D = 1/2$	0.56
$d/D = 3/4$	0.19
Sudden contraction:†	
From reservoir or from large cylinder	0.5
$d/D = 1/4$	0.42
$d/D = 1/2$	0.33
$d/D = 3/4$	0.19

† D = large diameter
 d = small diameter

G = flow rate, gpm
 s = specific gravity of liquid
 f = friction factor

The Crane Company has published a reference which discusses pressure loss calculations and presents valuable related data (Ref. 6).

2-10.1.2 Pressure Surges

The peak pressures in a hydraulic line occur when a hydraulic shock is generated by a sudden change in flow conditions such as the rapid closing of a valve. These pressure surges propagate through the distribution system at the local speed of sound. They are reflected from various internal surfaces until the kinetic energy of the original shock is dissipated by friction. Pressure surges are usually accompanied by vibration

and noise. The hydraulic lines and connectors must have sufficient strength to contain and suppress these shock-induced pressure surges. This capability may be a function of both pipe strength and line layout.

2-10.1.3 Pipe and Tubing Sizes

Standard dimensions of pipe and tubing are given in Tables 2-2 and 2-3, respectively.

2-10.2 HOSE, TUBING, AND PIPE FITTINGS

Pipe and tubing fittings can be either threaded or permanent. Permanent methods include various forms of brazing, welding, swaging, and adhesive bonding. Such assembly methods are applied where low initial cost, reliability, and weight are important factors.

Threaded pipe-fitting techniques include tapered pipe threads, flanges, SAE O-ring ports, and straight-thread ports with metal seals. Nonthreaded tube fittings can be of three types—flare, self-flare, or flareless. Flare fittings are illustrated in Fig. 2-74. Typical flareless fittings are shown in Fig. 2-75. Self-flare fittings incorporate a wedge-shaped sleeve which enlarges the tube ending when the nut is tightened.

Hose fittings are either permanent or reusable. High-pressure permanent fittings are factory-assembled on the hose. Reusable fittings are available with pressure ratings up to 5,000 psi. Self-sealing couplings are sometimes used with hose in hydraulic piping systems. The four basic self-sealing types—double poppet, sleeve and poppet, slide-seal, and double rotating ball—are illustrated in Fig. 2-76.

2-11 SHOCK ABSORBERS

Fluid power is often used to cushion or absorb the impact caused when a moving mass must be stopped. If the energy of the moving mass is to be dissipated, a shock absorber is used. The working fluid in a shock absorber can be a liquid, a gas, or a combination of the two. Shock absorbers are available in a variety of different designs and configurations.

Most shock absorbers, called nonregenerative shock absorbers, dissipate all of the energy of the moving mass. They rely on springs or other mechanisms to return the shock absorber to an equilibrium position. Common automobile shock absorbers are an example. However, there is an important class of shock absorbers, called hydropneumatic mechanisms, that use pneumatic power to return the shock absorber to

TABLE 2-2.
DIMENSIONS AND CHARACTERISTICS OF PIPE FOR HYDRAULIC SYSTEMS

Nominal Pipe Size, in.	Pipe OD, in.	No. of Threads, per in.	Schedule 40 Standard Pipe ID, in.	Schedule 80 Extra Heavy Pipe ID, in.	Schedule 160 Pipe ID, in.	Double Extra Heavy Pipe ID, in.
1/4	0.540	18	0.364	0.302	-----	-----
3/8	0.675	18	0.493	0.423	-----	-----
1/2	0.840	14	0.622	0.546	0.466	0.252
3/4	1.050	14	0.824	0.742	0.614	0.434
1	1.315	11-1/2	1.049	0.957	0.815	0.599
1-1/4	1.660	11-1/2	1.380	1.278	1.160	0.896
1-1/2	1.900	11-1/2	1.610	1.500	1.388	1.100
2	2.375	11-1/2	2.067	1.939	1.689	1.503
2-1/2	2.875	8	2.469	2.323	2.125	1.771
3	3.500	8	3.068	2.900	2.624	-----

TABLE 2-3.
WALL THICKNESS EQUIVALENTS

Birmingham or Stubs' Iron Wire Gage Size	Equivalent Tube Wall Thickness t, in.	Birmingham or Stubs' Iron Wire Gage Size	Equivalent Tube Wall Thickness t, in.
1	0.300	16	0.065
2	0.284	17	0.058
3	0.259	18	0.049
4	0.238	19	0.042
5	0.220	20	0.035
6	0.203	21	0.032
7	0.180	22	0.028
8	0.165	23	0.025
9	0.148	24	0.022
10	0.134	25	0.020
11	0.120	26	0.018
12	0.109	27	0.016
13	0.095	28	0.014
14	0.083	29	0.013
15	0.072	30	0.012

equilibrium. The operating principles of hydraulic shock absorbers and hydropneumatic mechanisms are discussed in the paragraphs which follow.

2-11.1 HYDRAULIC SHOCK ABSORBERS

A hydraulic shock absorber is normally used to completely stop a moving mass in a uniform manner. The shock absorber accomplishes the "smooth" deceleration by metering hydraulic fluid through orifices, converting work and kinetic energy into heat which is dissipated. The metering orifices may be fixed in size or adjustable so that deceleration rate may be varied.

A cross-sectional sketch of a typical shock absorber is shown in Fig. 2-77. When a moving mass strikes the bumper, the piston moves inward. The resisting pressure behind the piston closes the check valve. The piston then pushes the liquid through the metering orifices from the inner high-pressure chamber to the outer low-pressure chamber.

The resistance to the liquid flow caused by the orifices acts against the piston to slow its motion. As the piston moves inward, it progressively blocks the orifices, increasing the resistance and uniformly decelerating the mass.

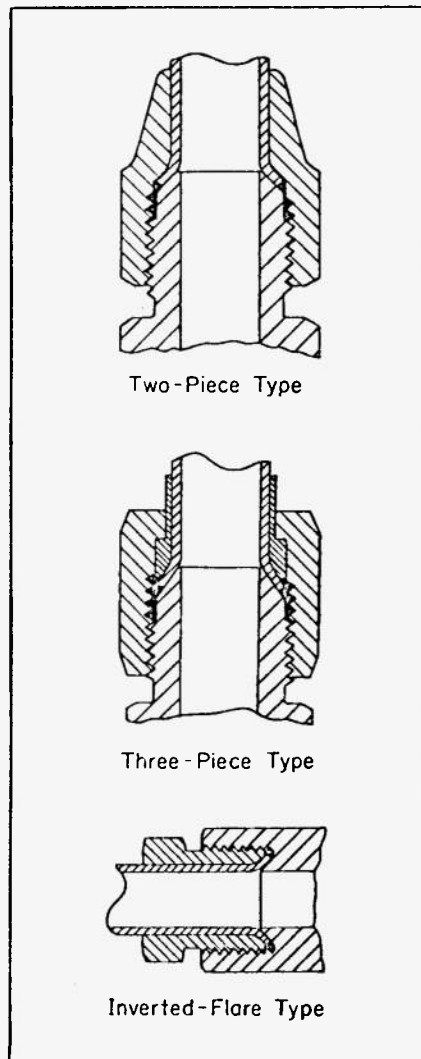


Fig. 2-74. Typical Flare Fittings for Hydraulic Tubing

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

2-11.2 HYDROPNEUMATIC SHOCK ABSORBERS

A hydropneumatic shock absorber works on essentially the same principle as the hydraulic shock absorber except that both a liquid and a gas are used as the working fluids. A simplified sketch of a hydro-pneumatic mechanism is shown in Fig. 2-78. As the mass to be stopped drives the piston inward, liquid metering through the orifices and compression of the gas brings the mass to a stop. The compressed gas then expands and returns the piston to the starting position. There are numerous variations of the hydropneumatic shock

absorber. Many designs have a separate cylinder or container for the gas. Hydropneumatic configurations similar to that shown in Fig. 2-78 are frequently used in aircraft landing gear struts and are referred to as oleo shock absorbers or oleo struts. Artillery recoil mechanisms, an important application of hydropneumatic shock absorbers, frequently use separate cylinders for the gas and the liquid. Several methods of driving the piston into the gas cylinder are used. Fig. 2-79 shows a simplified sketch of a recoil mechanism with separate pistons for each cylinder being driven by the same moving mass.

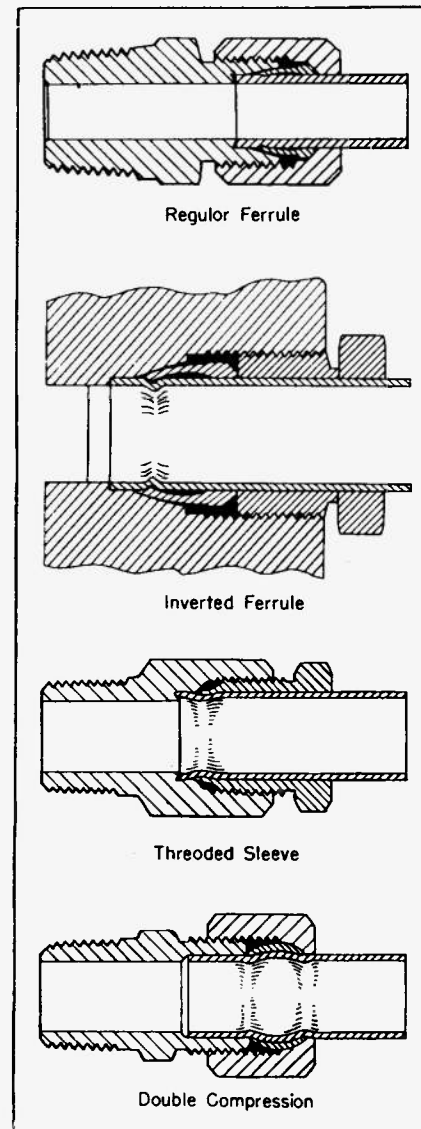
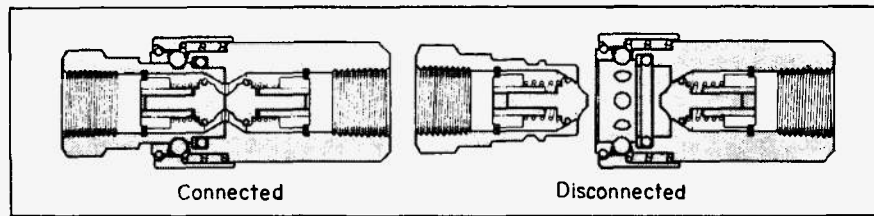
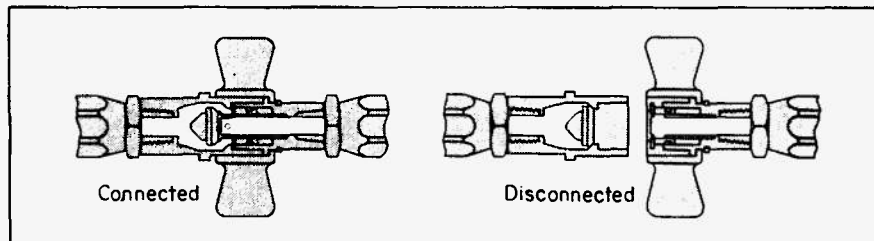


Fig. 2-75. Typical Flareless Fittings for Hydraulic Tubing

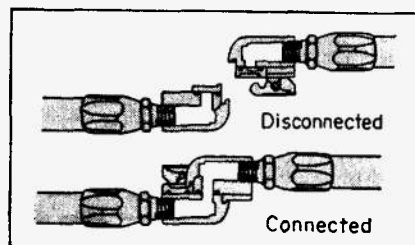
[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]



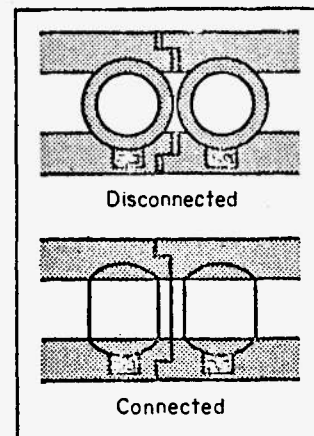
(A) Double Poppet



(B) Sleeve and Poppet



(C) Slide-seal



(D) Double Rotating Ball

Fig. 2-76. Typical Self-sealing Couplings for Hydraulic Hose

[From: Fluid Power Issue; *Machine Design*. Used by permission of Penton Publishing Co.]

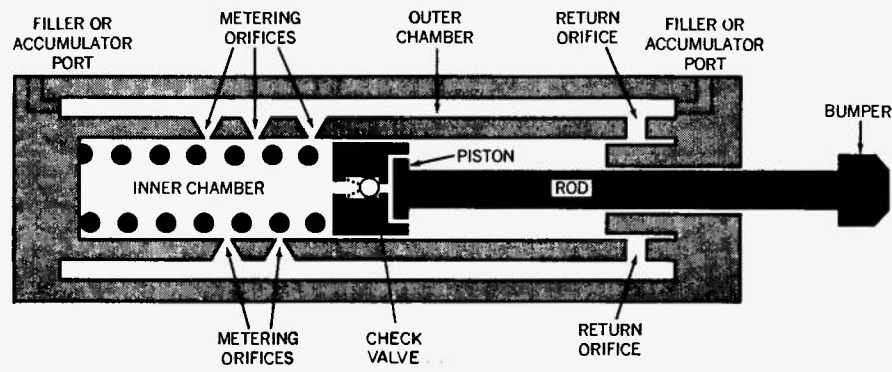


Fig. 2-77. Cross-sectional Sketch of a Typical Shock Absorber

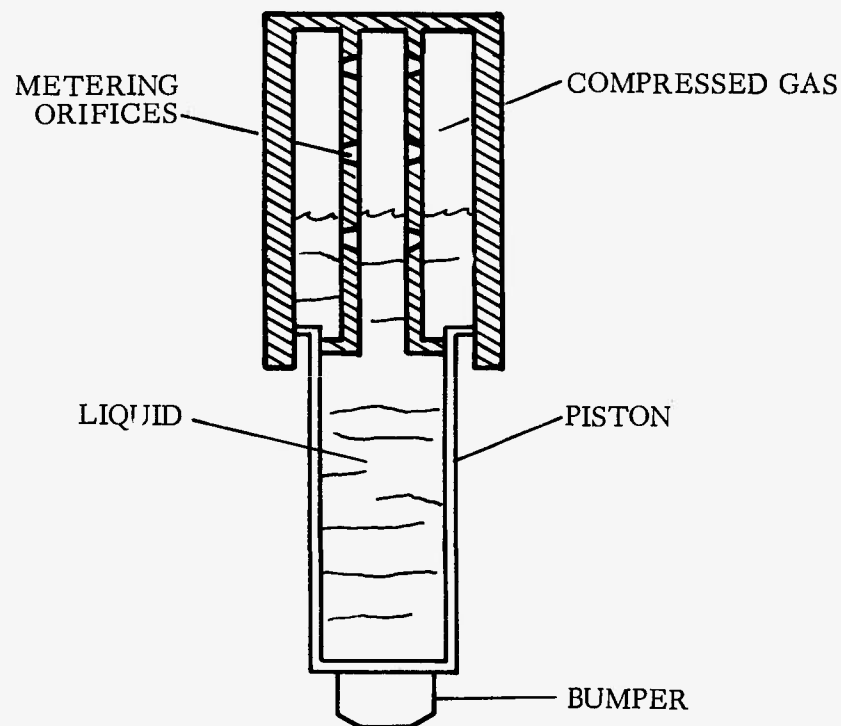


Fig. 2-78. Sketch of a Hydropneumatic Shock Mechanism

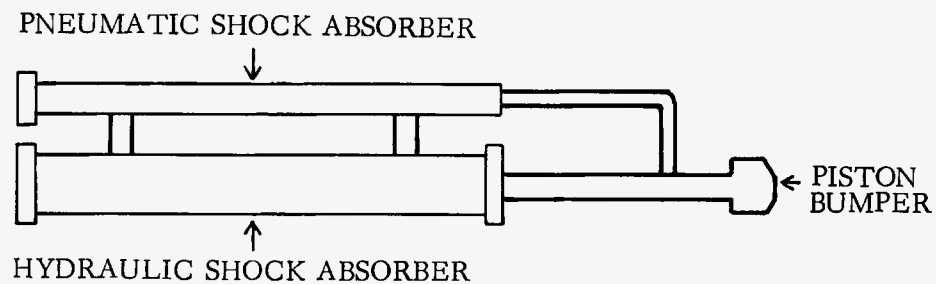


Fig. 2-79. Sketch of a Hydropneumatic Recoil Mechanism

2-11.3 HYDRAULIC FLUID PROPERTIES PERTINENT TO SHOCK ABSORBERS

Properties of a hydraulic fluid that are most pertinent to its use in shock absorbers are:

(1) *Bulk Modulus*: If the shock absorber is to be fully nonregenerative, the hydraulic fluid should have a high bulk modulus so that a minimum of energy would be stored in the fluid, producing springback of the shock absorber. A liquid spring (par. 2-12) stores all of its energy in the working liquid and would therefore require a low bulk modulus.

(2) *Density*: Use of a higher density working fluid would produce a shorter stroke but higher working pressures.

(3) *Viscosity*: The working liquid viscosity is a factor in the rate at which the fluid will pass through metering orifices—lower viscosity would mean faster rates and faster strokes. Also, the viscosity should be shear stable and not exhibit excessive changes with large temperature changes.

2-12 LIQUID SPRINGS

A liquid spring is a regenerative shock absorber that stops a moving mass and stores the energy of the mass in the spring. A liquid spring depends on the compressibility, or bulk modulus, of the liquid for its action. A liquid with a high compressibility is confined in a cylinder. When a ram is pushed into the cylinder, the liquid

is compressed and exerts a strong return force on the cylinder ram. Liquid springs provide high load-absorbing capacities in small packages. A single liquid spring can provide as much load-absorbing capacity as roughly 30 coil springs of the same length and diameter. They can be designed to reciprocate by providing little or no flow restriction or to act as a shock absorber or damper by restricting the flow with orifices in the piston. Disadvantages include high cost and sealing of resulting high pressures. Loads must be high before a liquid spring becomes practical.

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CHAPTER 3

FLUID PROPERTIES, SIGNIFICANCE, AND TEST METHODS

3-0 LIST OF SYMBOLS

A = area, in.² or cm²
 \bar{B}_o = isothermal secant bulk modulus at 0 psig and temperature t , psi
 \bar{B}_s = adiabatic (isentropic) secant bulk modulus, psi
 B_s = adiabatic (isentropic) tangent bulk modulus, psi
 B_{so} = sonic bulk modulus, psi
 \bar{B}_t = isothermal secant bulk modulus at pressure p and temperature t , psi
 B_t = isothermal tangent bulk modulus at pressure p and temperature t , psi
 C = speed of sound, cm/sec
 C_s = isentropic compressibility
 C_t = isothermal compressibility
 c_p = specific heat at constant pressure, cal/g-°C
 c_v = specific heat at constant volume, cal/g-°C
 D = diameter, in.
 d = length, cm or in.
 e = 2.71828, the base of natural logarithms
 E° = viscosity, Engler degrees
 F = force, lb or dyne
 H = viscosity at 100°F of a standard fluid of 100 Viscosity Index having the same viscosity at 210°F as the fluid whose Viscosity Index is to be calculated
 k = constant for a given oil and temperature, (psi)⁻¹
 L = viscosity at 100°F of a standard fluid of 0 Viscosity Index having the same viscosity at 210°F as the fluid whose

Viscosity Index is to be calculated

N = relative surface speed
 p = pressure, psi, psia, or psig
 R = rate of shear, sec⁻¹
 R_n = Reynolds number, dimensionless
 s = specific gravity
 S = shearing stress, psi or dyne/cm²
 t = temperature
 T = time, sec
 U = viscosity at 100°F of the fluid whose Viscosity Index is to be calculated
 V = velocity, cm/sec or ft/sec
 V_o = initial volume
 $V.I.$ = Viscosity Index, dimensionless
 VTC = viscosity temperature coefficient
 Z = fluid viscosity
 β = conversion factor
 Γ = ratio of bulk moduli or specific heats, dimensionless
 η = absolute viscosity, poise or centipoise (cp), dyne-sec/cm²
 ν = kinematic viscosity, stoke or centistoke (cSt), cm²/sec
 ρ = fluid density, g/cm³
 ρ_o = density at atmospheric temperature and pressure, g/cm³

3-1 GENERAL

The specific requirements of a hydraulic fluid are determined by the design of the hydraulic system and by the functions the system must perform. A liquid that is satisfactory as a hydraulic fluid in one application or system may be completely unsuitable in a second application or system. Therefore, in considering the properties required of a hydraulic fluid, it should be remembered that the relative importance of any one property

will depend upon the hydraulic system, its use, and its environment.

The various properties which are important in the selection and use of hydraulic fluids are presented in this chapter. Some properties may be important in all liquids, while others have significance only in limited applications. Properties are discussed in relation to their function in a hydraulic system. The importance of these properties is assessed, and methods for measuring them are given.

3-2 PHYSICAL PROPERTIES

3-2.1 VISCOSITY

Viscosity is one of the most important properties of a liquid from the standpoint of its performance in hydraulic systems. It is the resistance offered by a liquid to relative motion of its molecules or the resistance a liquid offers to flow. Temperature is the most important variable affecting viscosity and must be stated in all viscosity data.

Viscosity is defined by Newton's Law—at a given point in a liquid, the shearing stress S is directly proportional to the rate of shear R , i.e.,

$$S = \eta R \quad (3-1)$$

The proportionality constant η is known as the coefficient of viscosity or simply the viscosity. Since for the relative motion of two parallel layers of liquid the shearing stress is equal to F/A , where F is the force and A is the area, and since the rate of shear is equal to V/d where V is the velocity and d is the distance between the layers (see Fig. 3-1), Eq. 3-1 may be written as

$$\frac{F}{A} = \eta \left(\frac{V}{d} \right) \quad (3-2)$$

or

$$\eta = \frac{Fd}{AV} \quad (3-3)$$

3-2.1.1 Absolute Viscosity

The viscosity η defined by Eq. 3-3 is the absolute or

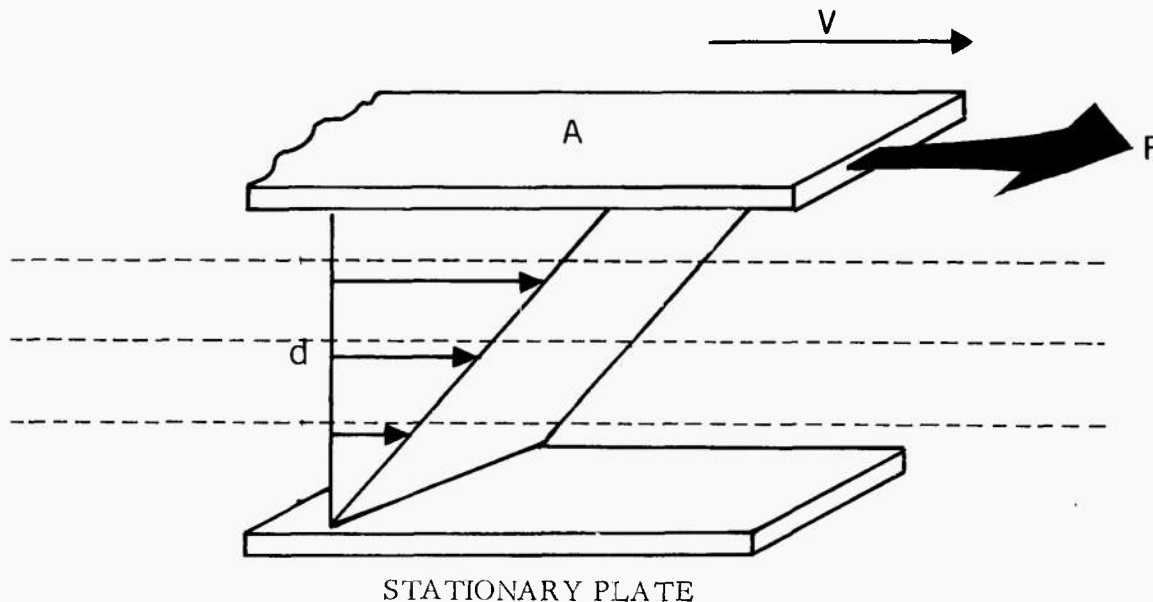


Fig. 3-1. Velocity Distribution in a Liquid Between Two Parallel Plates With the Top Plate Moving With Respect to the Stationary Bottom Plate

dynamic viscosity. If the metric system of units (centimeter, gram, second) is used, the unit of absolute viscosity is the dyne-second per square centimeter or the poise. Because the poise is a rather large unit, the centipoise (one hundredth of a poise) is customarily used. Pure water at a temperature of 20.2°C (68.4°F) has an absolute viscosity of one centipoise. If the English system of units (foot, pound, second) is used, the unit of absolute viscosity is the pound-second per square inch or the reyn. Since the reyn is an extremely large unit, the newton (one millionth of a reyn) is more convenient. Conversion between metric and English system units of absolute viscosity can be made on the basis that one reyn (or one million newtons) is equal to 68,950 poises (or 6,895,000 centipoises).

3-2.1.2 Kinematic Viscosity

The ratio of the absolute viscosity of a liquid to its density frequently occurs in the study of viscosity and hydraulics and the term "kinematic viscosity" with the symbol ν has been assigned to it

$$\nu = \frac{\eta}{\rho} \quad (3-4)$$

where ρ is the density. In the metric system, the unit of kinematic viscosity is the square centimeter per second or the stoke. The centistoke (one hundredth of a stoke) is more generally used. The kinematic viscosity of a liquid can be looked upon as the liquid's resistance to flow under its own gravity head.

3-2.1.3 Other Viscosity Scales

Numerous other scales of viscosity have been established which express viscosity in terms of arbitrary units based on the instruments used to make the measurement. The five most common scales used in the petroleum industry are the Saybolt Universal and Saybolt Furol used mainly in the United States, the Redwood No. 1 (Standard) and Redwood No. 2 (Admiralty) used in Great Britain, and the Engler used chiefly in Germany and other countries in Europe. All five are empirical instruments in that the time of outflow of an arbitrary constant amount of liquid through a fixed orifice is quoted as a measurement of the viscosity of the liquid. The instruments are similar, but various dimensions and amounts of liquid used assign different viscosity numbers to the same fluid; therefore, the viscosity is meaningful only when the instrument and temperature are also named (Ref. 1).

The Saybolt Universal and Saybolt Furol viscosity scales, used extensively in the United States, give viscosity in terms of seconds—Saybolt Universal Seconds (SUS) or Saybolt Furol Seconds (SFS). A Furol viscosity is approximately one-tenth of the Universal viscosity for the same liquid at the same temperature. The Furol scale is used chiefly for petroleum products having viscosities greater than 1,000 SUS, such as heavy fuel and road oils.

3-2.1.4 Viscosity Unit Conversions

A viscosity determined in a particular instrument at a specific temperature can be converted to the equivalent viscosity in some other instrument at the same temperature. A wide variety of equations, tables, charts, and nomographs have been developed to facilitate such conversions. Currently, the trend is toward expressing viscosity in the metric units of centipoises (cp) and centistokes (cSt). Data in convenient tabular form for the conversion of kinematic viscosity to Saybolt Universal and Saybolt Furol viscosity are provided in American Society for Testing Materials (ASTM) Method D-2161-66 (Ref. 2). Procedures for converting the five more common viscosity scales to the metric scale in centistokes are described.

(1) Saybolt Universal seconds to centistokes:

$$\nu = 0.226 T - \frac{195}{T}, 32 \leq T \leq 100 \text{ sec} \quad (3-5)$$

(T = efflux time in seconds)

$$\nu = 0.220 T - \frac{135}{T}, T > 100 \text{ sec} \quad (3-6)$$

(2) Saybolt Furol seconds to centistokes:

$$\nu = 2.24 T - \frac{184}{T}, 25 \leq T \leq 40 \text{ sec} \quad (3-7)$$

$$\nu = 2.16 T - \frac{60}{T}, T > 40 \text{ sec} \quad (3-8)$$

(3) Redwood No. 1 (Standard) seconds to centistokes:

$$\nu = 0.260 T - \frac{179}{T}, 34 \leq T \leq 100 \text{ sec} \quad (3-9)$$

$$\nu = 0.247 T - \frac{50}{T}, T > 100 \text{ sec} \quad (3-10)$$

(4) Redwood No. 2 (Admiralty) seconds to centistokes:

$$\nu = 2.46 T - \frac{100}{T}, 32 \leq T \leq 90 \text{ sec} \quad (3-11)$$

$$\nu = 2.45 T, T > 90 \text{ sec} \quad (3-12)$$

(5) Engler Degrees (E°) to centistokes:

$$\nu = 8.0 E^\circ - \frac{8.64}{E^\circ}, 1.35 \leq E^\circ \leq 3.2 \quad (3-13)$$

$$\nu = 7.6 E^\circ - \frac{4.0}{E^\circ}, E^\circ > 3.2 \quad (3-14)$$

3-2.1.5 Newtonian Fluids

When a liquid flows in such a manner that the shearing stress S is directly proportional to the rate of shear (see par. 3-2.1), the liquid is said to flow in accordance with Newton's Law and is called a Newtonian fluid. Flow of this type is known as "viscous" or "streamline" flow. Viscous flow consists of an orderly motion in which layers of liquid slide past one another in a direction parallel to the direction of flow. The viscosity η is constant with respect to the rate of shear R (see Fig. 3-2). Most hydraulic fluids behave in a Newtonian, or nearly Newtonian, manner at the temperatures, pressures, and flow rates normally encountered in hydraulic systems. However, there are some types of materials that are never Newtonian, and most Newtonian fluids can be made to behave in a non-Newtonian manner by changing the pressure, temperature, and/or flow rate sufficiently (Ref. 3). Non-Newtonian materials are discussed in the paragraphs which follow.

3-2.1.6 Non-Newtonian Materials

The viscosities of some materials are altered by shearing effects and these materials are termed "non-Newtonian". The viscosity depends on the rate of shear at which it is measured. Since a non-Newtonian fluid can have an unlimited number of viscosities (as the shear rate is varied), the term "apparent viscosity" is used instead of viscosity. Apparent viscosity is expressed in units of absolute viscosity, and the rate of shear used in the measurement is given.

3-4

NEWTONIAN FLUID

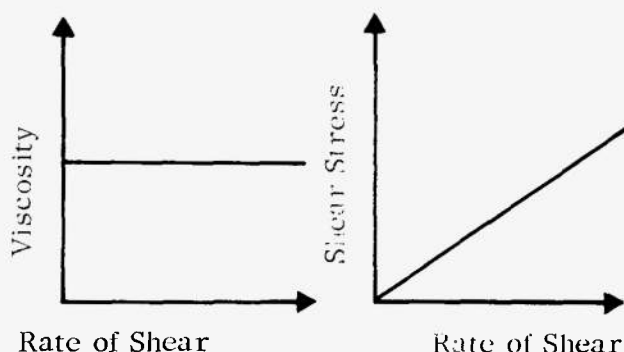


Fig. 3-2. Viscosity and Shear Stress Curves for a Newtonian Fluid

Non-Newtonian materials may be classified into five types—plastic, pseudoplastic, dilatant, thixotropic, and rheopectic.

(1) *Plastic*. A definite minimum stress or force must be applied to this type of material before any flow occurs, and viscosity decreases as shear rate increases (see Fig. 3-3). Examples of such materials are putty, molding clay, and many types of greases.

PLASTIC

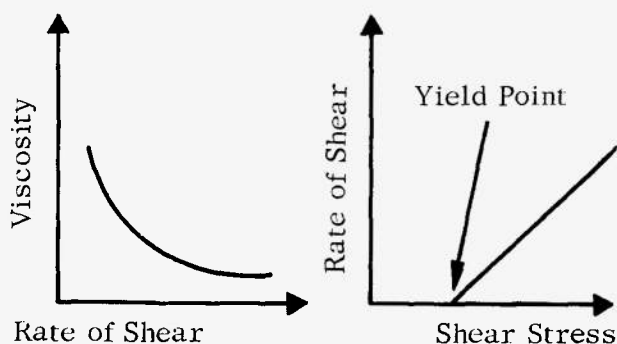


Fig. 3-3. Viscosity and Shear Stress Curves for a Plastic Material

(2) *Pseudoplastic*. This type of material has no fixed yield point; however, the viscosity does decrease with increasing shear rates (see Fig. 3-4). Examples of such materials are water base liquids and resinous materials.

(3) *Dilatant*. The apparent viscosity of this type of material increases as the rate of shear increases, and the material will often solidify at high rates of shear (see

Fig. 3-5). However, when the applied force is removed, the material reverts to its original state, i.e., liquid. Examples of dilatant materials are pigment-vehicle suspensions—such as paints and printing ink—and some starches.

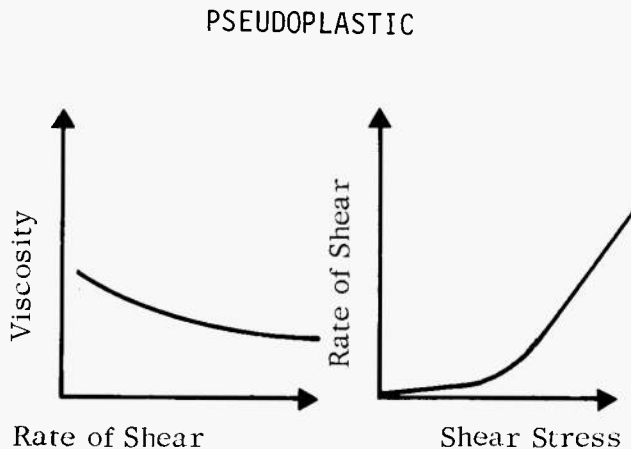


Fig. 3-4. Viscosity and Shear Stress Curves for a Pseudoplastic Material

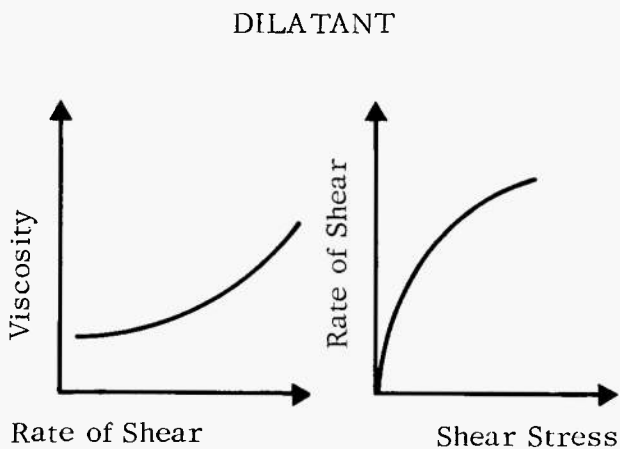


Fig. 3-5. Viscosity and Shear Stress Curves for a Dilatant Material

(4) *Thixotropic*. The viscosity of this type of material is time-dependent—if it is subjected to a constant rate of shear, its structure breaks down, and its apparent viscosity decreases to some minimum value (see Fig. 3-6). However, when the applied force is removed, the material reverts to its original state, i.e., gelled. Paints are probably the most notable example of thixotropic materials. Quicksand is also thixotropic.

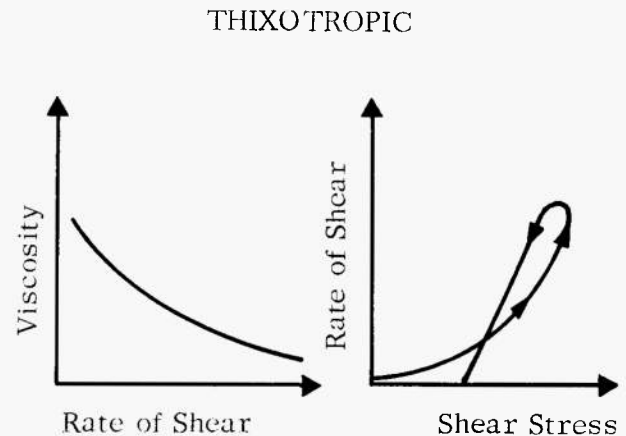


Fig. 3-6. Viscosity and Shear Stress Curves for a Thixotropic Material

(5) *Rheopectic*. This type of material is similar to the thixotropic materials except that the apparent viscosity increases with shearing time up to some maximum value (see Fig. 3-7). Some bearing greases are manufactured with this property to facilitate pumping into containers in a less viscous state, but to increase in viscosity when in use in a bearing. However, many such greases are not true rheopectic materials as they do not revert to their original state after the applied force is removed but retain a somewhat higher viscosity.

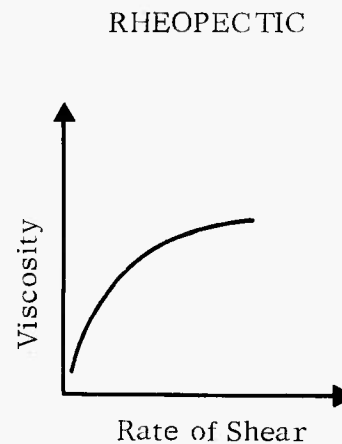


Fig. 3-7. Viscosity and Shear Stress Curves for a Rheopectic Material

3-2.1.7 Determination of Viscosity of Non-Newtonian Materials

As shown in Fig. 3-8, the determination of the viscosity of a non-Newtonian fluid at only one shear rate

is not usually sufficient. The viscosity of the Newtonian and non-Newtonian fluids shown have the same value at a shear rate R_0 . Incorrect comparisons and application difficulties would be invited if the viscosities at only this point were specified.

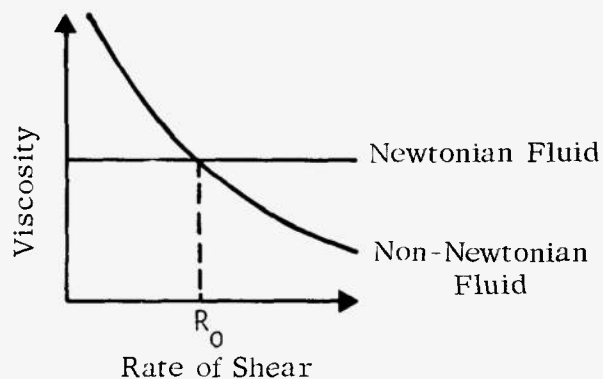


Fig. 3-8. Viscosity Curves for a Newtonian Fluid and a Non-Newtonian Fluid

3-2.1.8 Turbulent Flow and Reynolds Number

If the flow velocity of a Newtonian fluid is increased beyond some critical value, the flow characteristics begin to change. The critical velocity marks the transition between viscous flow, where the liquid follows Newton's Law, and turbulent flow, where the liquid does not behave in a Newtonian fashion. Viscous flow is an orderly motion of the liquid in the direction of flow. Turbulent flow, however, is an erratic flow with eddy currents (see Fig. 3-9). Reynolds has shown that the critical velocity depends upon the dimensionless parameter known as the Reynolds number (Ref. 3). For flow in pipes, Reynolds number R_n is given by:

$$R_n = \frac{DV\rho}{\nu} \quad (3-15)$$

where

- D = pipe diameter
- V = fluid velocity
- ρ = fluid density
- ν = kinematic viscosity

When the Reynolds number is sufficiently low, the flow is viscous and the liquid behaves in a Newtonian manner. The transition to turbulent flows usually occurs between Reynolds number values of 2,100-4,000—depending upon the geometry of the conduit and the liquid properties.

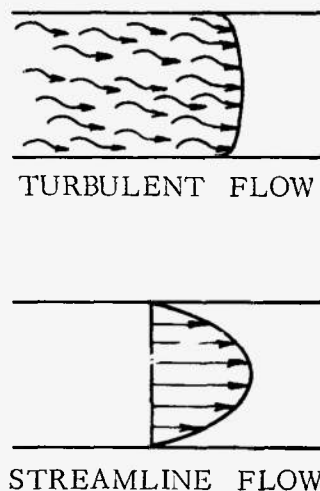


Fig. 3-9. Streamline Flow and Turbulent Flow in a Pipe

3-2.1.9 Measurement of Viscosity

Liquid viscosity is measured by an instrument called a viscometer. A large number of viscometers have been developed. Eight of the most common measurements upon which viscometers are based are (Ref. 4)

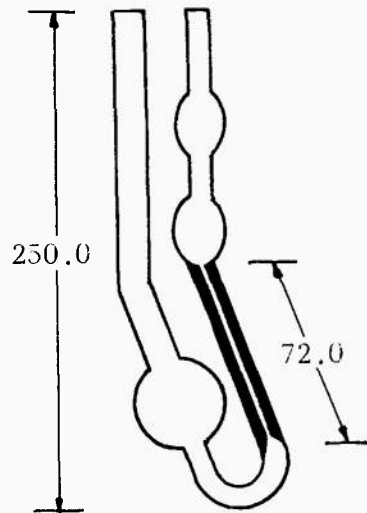
- (1) The time of flow of a quantity of liquid through a capillary or a short tube, using gravity as the moving force.
- (2) The torque required to rotate a cylinder, disk, or paddle in a liquid at constant speed
- (3) The torque exerted on a disk suspended in a rotating cup of the liquid
- (4) The rotational speed of a cylinder or disk driven in the liquid by a constant torque
- (5) The time of fall through the liquid of a ball or cylindrical object
- (6) The time of rise of an air bubble through the liquid
- (7) The rate of damping of ultrasonic waves induced in the liquid
- (8) The pressure drop through a capillary.

The most widely used viscometers in the petroleum industry are the capillary and the short tube viscometers. ASTM D-445-65 (Ref. 5) prescribes the standard procedure for measuring kinematic viscosity and describes the capillary viscometers that are to be used. Briefly, the method calls for measuring the time of flow of a known quantity of liquid at a constant temperature through a capillary with gravity as the only moving force, and multiplying the time by a calibration constant. The calibration constant is determined by using a master viscometer (Bureau of Standards) and standard oils. Absolute viscosity is given by the equation

$$\eta = \nu\rho \quad (3-16)$$

A separate determination of the density ρ must be made before calculating the absolute viscosity. ASTM D-445-65 (Ref. 5) lists several approved test procedures for determining density.

The Cannon-Fenske capillary viscometer (see Fig. 3-10) is the most common one used in hydraulic fluid work. A cross section of the Saybolt viscometer, widely used in the petroleum industry, is shown in Fig. 3-11.



(dimensions in millimeters)

Fig. 3-10. Cannon-Fenske Capillary Tube Viscometer

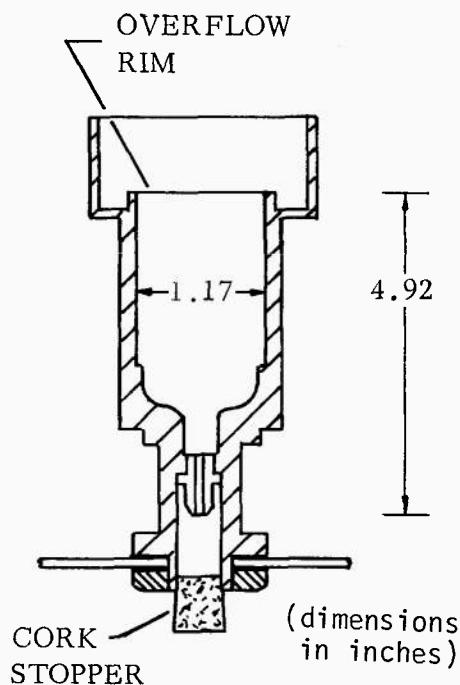


Fig. 3-11. Cross-sectional View of a Saybolt Viscometer

3-2.1.10 Significance of Viscosity

The single most important property of a hydraulic fluid is its viscosity. Various components within a hydraulic system have competing requirements as to high or low viscosity. High viscosity provides thick lubricating films and reduces internal leakage. Low viscosity results in less internal friction, smaller pressure losses in pipes and valves, and an increase in control action and component response. Thus, a compromise in viscosity requirements must be made. The viscosity of the hydraulic fluid affects the response of system components, and because its sensitivity to temperature usually imposes limitations on the upper or lower operating temperature of any hydraulic system, viscosity must always be considered in design calculations.

3-2.1.11 Test Methods for Viscosity

(1) Kinematic Viscosity

Test Methods: Federal Test Method 305.4 (Ref. 6)
ASTM D-445-65 (Ref. 5)

These methods describe the procedure for determining the kinematic viscosity of transparent or opaque fluids higher than 0.2 centistoke. Determinations may be made at temperatures where the flow in the glass capillary type viscometers is Newtonian. The time is measured for a fixed volume of a test fluid to flow through the capillary under a gravity head and at a closely controlled temperature. The kinematic viscosity is then calculated from the efflux time and the viscometer calibration factor.

Precision: For clean transparent oils tested at 100° and 210°F, results should not be considered suspect unless they differ by more than the following amounts:

- Repeatability-0.35 percent of mean
- Reproducibility-0.7 percent of mean

(2) Saybolt Viscosity

Test Methods: Federal Test Method 304.8 (Ref. 7)
ASTM D-88-56 (Ref. 8)

These methods describe the procedure for determining the Saybolt viscosity of petroleum products in the temperature range of 70° to 210°F. The efflux time in seconds of 60 ml of the sample flowing under gravity head through a calibrated orifice is measured under carefully controlled temperature conditions. A Universal orifice is used for Saybolt Universal viscosity and a Furol orifice is used for Saybolt Furol viscosity. The time is corrected by an orifice factor and reported as the viscosity of the sample at the test temperature in Saybolt Universal Seconds (SUS) or Saybolt Furol Seconds (SFS). Viscosity values below 200 sec are reported to

the nearest 0.1 sec. Values above 200 sec are reported to the nearest whole second.

(3) *Conversion of Kinematic Viscosity to Saybolt Universal Viscosity or to Saybolt Furol Viscosity*

Test Methods: Federal Test Method 9101.3 (Ref. 9)
ASTM D-2161-66 (Ref. 10)

These methods provide conversion tables and equations for converting viscosity in centistokes at any temperature to Saybolt Universal Seconds at the same temperature; and also for converting viscosity in centistokes at 122° and 210°F to Saybolt Furol Seconds at the same temperature.

(4) *Calibration of Master Viscometers and Viscosity Oil Standards*

Test Method: ASTM D-2162-64 (Ref. 11)

This method covers procedures for calibrating master viscometers and viscosity oil standards, both of which may be used to calibrate routine viscometers used in the determination of kinematic viscosity (Ref. 5). Master viscometers are calibrated with water at 68°F (20°C). They are then used to calibrate viscosity oil standards, i.e., stable Newtonian liquids.

Specifications, dimensions, and operating instructions are given for the following types of viscometers:

- (a) **Modified Ostwald Viscometers:** Cannon-Fenske routine, Cannon-Manning semi-micro, Pinkevitch, Zeitfuchs, SIL, BS/U-tube, BS/U miniature
- (b) **Suspended-level Viscometers:** Ubbelohde, Fitzsimons, Atlantic, BS/IL/SL, BS/IP/SL(S), BS/IP/MSL, Cannon-Ubbelohde, Cannon-Ubbelohde semi-micro.
- (c) **Reverse-flow Viscometers:** Cannon-Fenske opaque, Zeitfuchs Cross-arm, BS/IP/RF, Lantz-Zeitfuchs.

(5) *Glass Kinematic Viscometers*

Test Method: ASTM D-2515-66 (Ref. 12)

This method provides specifications for glass capillary-type kinematic viscometers suitable for use in the ASTM Test Method for kinematic viscosity (Ref. 5). A Cannon-Master viscometer is shown in Fig. 3-12.

3-2.2 VISCOSITY-TEMPERATURE PROPERTIES

Temperature is the most important factor affecting viscosity. Viscosity decreases with increasing temperature, but the rate of decrease depends upon the structure and chemical composition of the liquid. The amount of the decrease depends primarily upon the

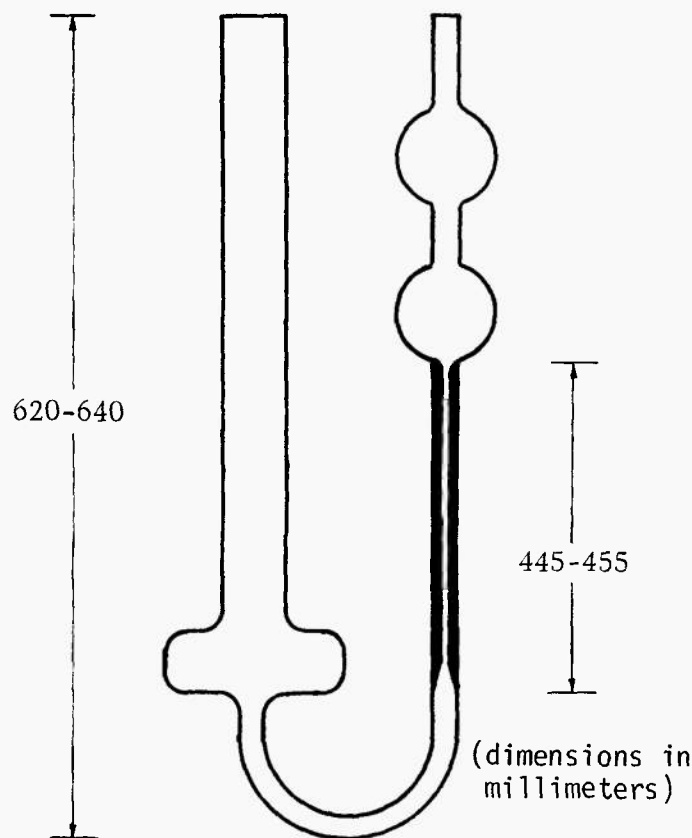


Fig. 3-12. Cannon-Master Viscometer

magnitude of the temperature change. Most components of a hydraulic system are quite specific in their demands for a particular viscosity at their operating temperature. This operating temperature rarely coincides with the fixed temperatures that are standard in the test methods for viscosity. To match the viscosity of a liquid to the requirements of a component requires a knowledge of the viscosity-temperature characteristics of the liquid over its usable temperature range.

Petroleum liquids described by Military Specifications are available for use within various temperature ranges. Some are usable to -80°F and others to +550°F. Increases in the upper temperature limit of petroleum liquids have been obtained by special processing or with additives. The development of liquids suitable for use in high-temperature environments is one of the prime areas of current interest in the hydraulic fluid industry. Properties of available high-temperature liquids will be discussed in greater detail in Chapter 4. Viscosity requirements at various temperatures of several typical Military Specification hydraulic fluids are given in Table 3-1.

TABLE 3-1.
VISCOSITY REQUIREMENTS OF FIVE SPECIFICATION HYDRAULIC FLUIDS*

Temperature, °F	MIL-H-5606B	MIL-H-8446B	MIL-H-13866B (MR)	VV-B-680a	MIL-H-27601A
-65	3000 (max)	2500 (max)			To be reported
-40	500 (max)				4000 (max)
-30			4200 (max)	1800 (max)	
100		To be reported	55 (min)	3.5 (min) at 122°F	385 (max) at 0°F
130	10.0 (min)				
210		To be reported	15 (min)	1.3 (min) at 212°F	3.2 (min)
400		2.5 (min)			Report at 500°F

*All viscosities in centistokes.

References: MIL-H-5606B; *Hydraulic Fluid, Petroleum Base, Aircraft, Missile, and Ordnance.*
MIL-H-8446B; *Hydraulic Fluids, Nonpetroleum Base, Aircraft.*
MIL-H-13866B; *Hydraulic Fluid, Petroleum Base, Artillery Recoil, Special.*
VV-B-680a; *Brake Fluid, Automotive.*
MIL-H-27601A; *Hydraulic Fluid, Petroleum, High Temperature, Flight Vehicle.*

3-2.2.1 ASTM Viscosity-temperature Charts

Many systems have been developed for expressing the viscosity-temperature characteristics of liquids. The most widely used procedure utilizes the viscosity-temperature charts published by ASTM (see Fig. 3-13). These charts, available from ASTM, are described in an ASTM Method (Ref. 13) and in a Federal Test Method (Ref. 14). Five different viscosity-temperature charts similar to that shown in Fig. 3-13 are available with various temperature ranges and either kinematic or Saybolt Universal viscosity scales. These charts are constructed so that the plot of viscosity vs temperature is a straight line for most petroleum liquids. Thus, only two viscosity measurements, usually at 100° and 210°F, need to be made to determine a line from which the approximate viscosity at any other temperature can be read.

The viscosity-temperature charts are useful for predicting viscosity only when the graph for a liquid is linear. In most instances this will occur over the temperature range that a given liquid is Newtonian. However, many Newtonian petroleum liquids will deviate from linearity at low viscosities, i.e., high temperature. Many liquids deviate from linearity near their cloud points (par. 3-2.6.2) because of the formation of wax particles. For non-Newtonian liquids, and for Newtonian liquids that are in nonlinear conditions of behavior, the plot of viscosity vs temperature cannot be used

to predict viscosity. The actual viscosity-temperature properties of the liquid must be determined and plotted.

The ASTM charts are based on a modified Walther equation:

$$\log [\log (\nu + c)] = A \log ^{\circ} R + B \quad (3-17)$$

where

c = a constant
 $^{\circ} R$ = temperature, °Rankine
 ν = viscosity, cSt
 A, B = constants for each fluid

The ASTM chart expresses c as a constant varying from 0.75 at 0.4 cSt to 0.6 at 1.5 cSt and above (Ref. 15). The use of this equation in chart form obviates the necessity of determining the constants A and B when two or more viscosities are determined experimentally and plotted.

3-2.2.2 ASTM Slope

A simple method of expressing a change in viscosity with temperature is by using the slope of the curve on the ASTM charts. Since the curve accurately portrays the viscosity-temperature characteristics of a particular liquid, its slope is a measure of the liquid's sensitivity to a change in temperature. The slope may be determined graphically from the chart as the tangent of the angle formed by the viscosity-temperature line and the

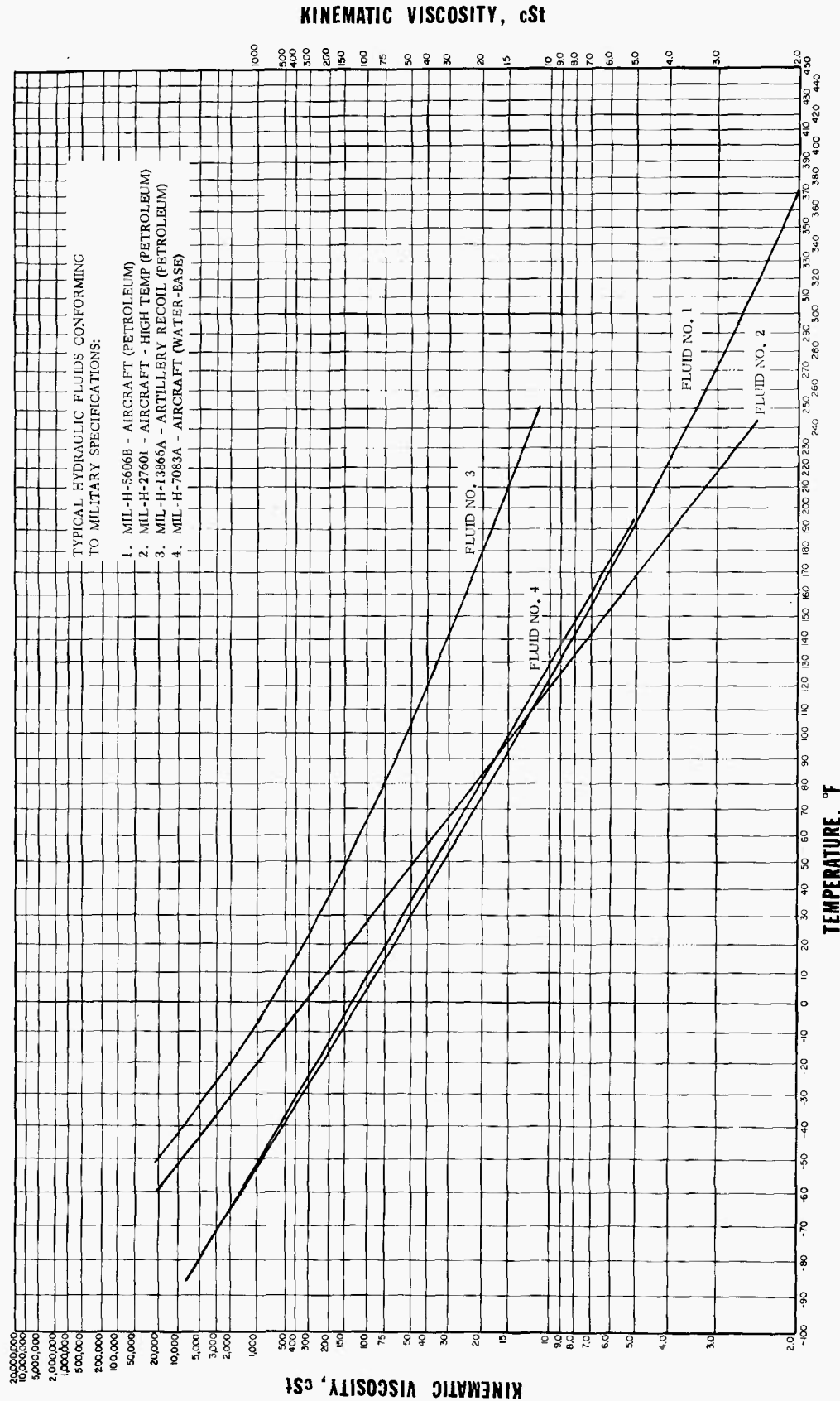


Fig. 3-13. Viscosity-temperature Graphs of Four Military Specification Hydraulic Fluids

lines of constant viscosity (see Fig. 3-14). The slope values are unitless and negative, but by convention the minus sign is omitted. The greater the slope, the greater the change in viscosity for a given change in temperature. If the slope is determined at a temperature where the graph is not a straight line, the slope of the tangent to the curve at the temperature in question is used.

The ASTM slope is easily determined and values accurate to within ± 0.01 slope units can be obtained by use of the chart and a simple ruler. However, the slope has little physical meaning and has not been adopted for general use.

3-2.2.3 Viscosity-temperature Coefficient

Another way of expressing the viscosity-temperature relationship of a liquid is the viscosity-temperature coefficient (*VTC*) which is defined by

$$VTC = \frac{\nu_{100} - \nu_{210}}{\nu_{100}} = 1 - \frac{\nu_{210}}{\nu_{100}} \quad (3-18)$$

where ν_{100} and ν_{210} are the kinematic viscosities in centistokes of the liquid at 100° and 210°F, respectively. The *VTC* has the advantage of expressing the viscosity-temperature characteristics of a liquid as a number, but by definition, is applicable only to the temperature range of 100° to 210°F. It has not found wide use in the hydraulic fluid industry.

3-2.2.4 Viscosity Index

The Viscosity Index (*V.I.*) of a liquid is a number indicating the effect of a change in temperature on viscosity. A low *V.I.* signifies a relatively large change of viscosity with temperature. A high *V.I.* signifies a relatively small change of viscosity with temperature. The convenience afforded by the use of a single number to express the viscosity-temperature characteristics of a liquid has resulted in the widespread adoption of the viscosity index system in the petroleum industry.

The *V.I.* is an empirical scale using two series of petroleum fractions as standards. One fraction which seemed to have minimum viscosity-temperature sensitivity was arbitrarily assigned a *V.I.* of 100. The other fraction with maximum viscosity-temperature sensitivity was assigned a *V.I.* of zero. At the time the index scale was developed, all other petroleum fractions were expected to fall within the zero to 100 limits.

Subsequently, however, solvent refining, the use of additives, and synthetics have produced materials that are outside the *V.I.* scale in both directions.

The *V.I.* of a liquid with a given viscosity at 210°F is calculated by relating its viscosity at 100°F to the viscosity at 100°F for each of the standard fractions having a viscosity at 210°F equal to that of the unknown at 210°F. The *V.I.* is calculated by the following equation:

$$V.I. = \left(\frac{L - U}{L - H} \right) 100 \quad (3-19)$$

where

- L = viscosity at 100°F of a petroleum fraction of 0 *V.I.* having the same viscosity at 210°F as the fluid whose *V.I.* is to be calculated
- H = viscosity at 100°F of a petroleum fraction of 100 *V.I.* having the same viscosity at 210°F as the fluid whose *V.I.* is to be calculated
- U = viscosity at 100°F of the fluid whose *V.I.* is to be calculated

An ASTM Method (Ref. 16) and a Federal Test Method (Ref. 17) provide tables of values for L , H , and $(L - H)$ for determining the *V.I.* of a liquid from either the centistoke or the Saybolt viscosities at 100° and 210°F. A schematic representation of *V.I.* is shown in Fig. 3-15.

The *V.I.* scale as described has been in general use in the United States although it had a number of deficiencies. For many years the procedure used to calculate the *V.I.* was given by ASTM D-567-53 (Ref. 18) which has since been replaced because of the anomalies that resulted from use of the method. Some of the problems experienced were

- (1) It was based on arbitrary standards.
- (2) The system broke down for light oils having viscosities below about 8 cSt at 210°F.
- (3) In the range above *V.I.* of 125, the scale became meaningless since two oils that have equal viscosity at 100°F but widely different viscosities at 210°F may have the same *V.I.*
- (4) *V.I.* is not an additive property. The *V.I.* of an oil blend cannot be determined by manipulation of the *V.I.* of the individual components, particularly when widely different types of liquids are involved.

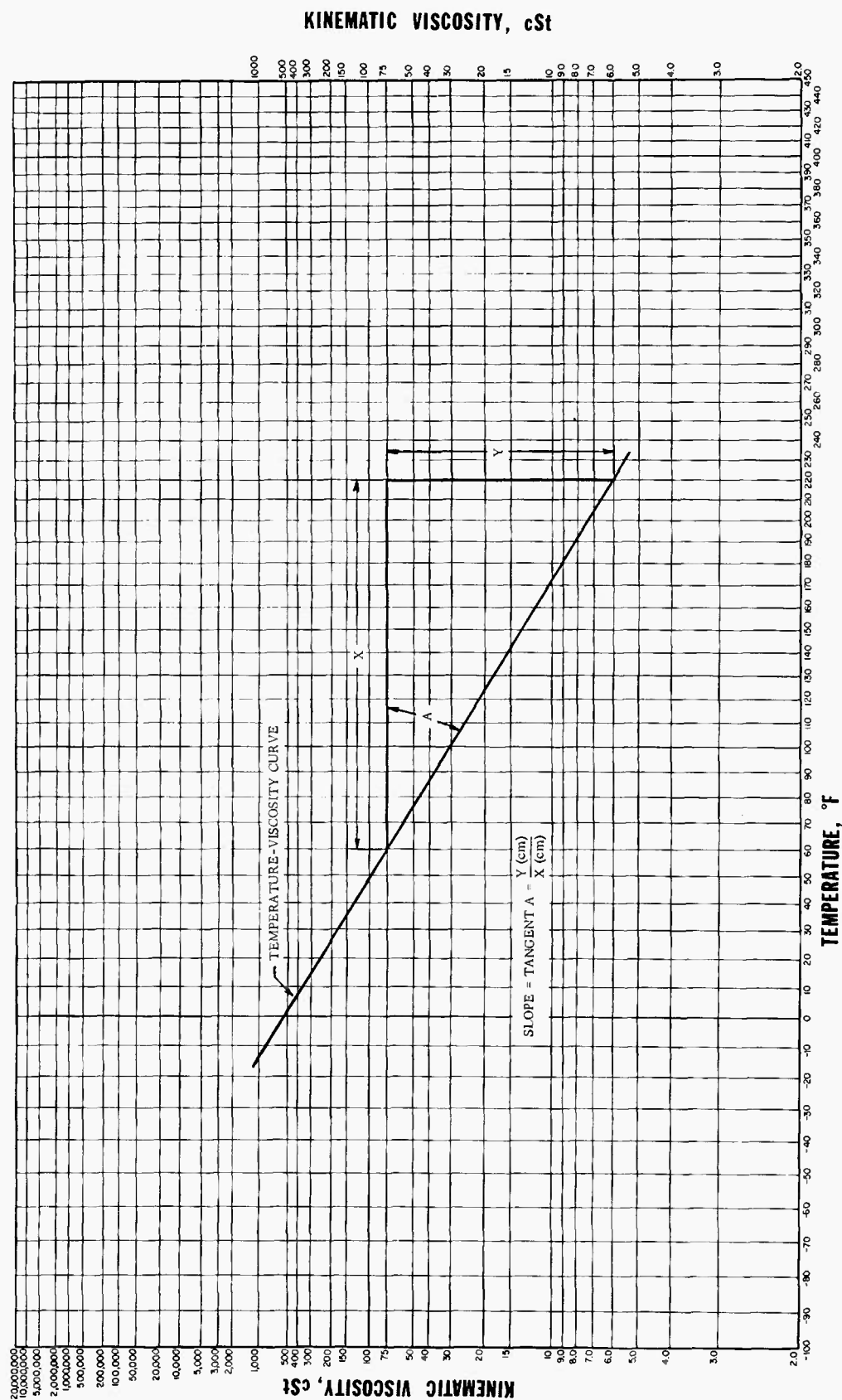


Fig. 3-14. Method of Calculating the ASTM Slope of a Hydraulic Fluid

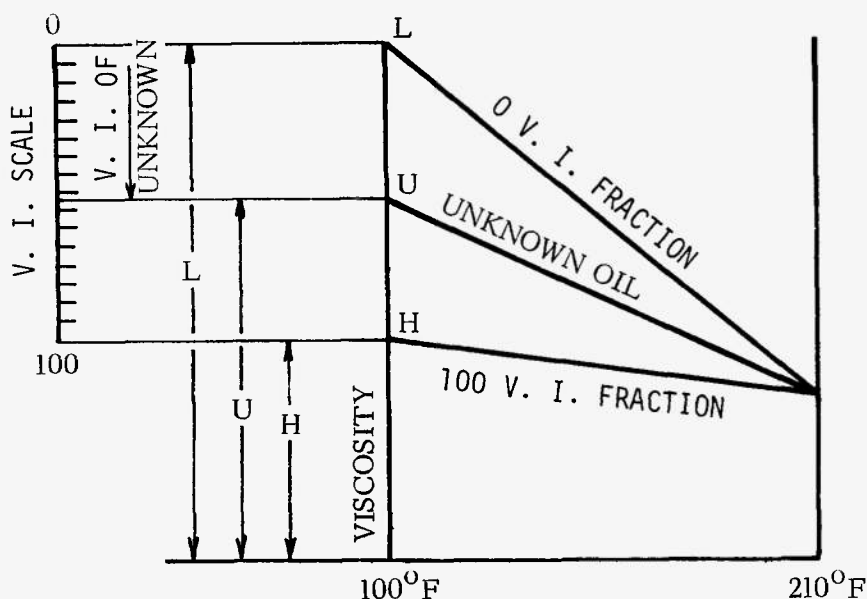


Fig. 3-15. Schematic Representation of Viscosity Index (V.I.)

[From: *Lubrication*, Vol. 47 (1961). Used by permission of Texaco, Inc.]

In spite of its shortcomings, the *V.I.* remains the most popular system for expressing viscosity-temperature characteristics of fluids. Numerous suggestions have been proposed to eliminate the shortcomings of the system or to find a more fundamental means of expressing viscosity-temperature characteristics. Most of the suggested systems were too complex for general use or had faults of their own, so a method (Refs. 16, 17) was developed to correct the deficiencies in the ASTM *V.I.*'s above 100 without shifting the values between 0 and 100. Values above 100 are designated Viscosity Index Extended (*V.I.E.*) (Ref. 19) to distinguish them from values obtained by the previous method.

3-2.2.5 Test Methods for Viscosity-temperature Properties

(1) Viscosity-temperature Charts

Test Methods: ASTM D-341-43 (Ref. 13)

Federal Test Method 9121.1 (Ref. 14)

- These methods provide specifications for standard viscosity-temperature charts (e.g., Fig. 3-13) for petroleum fluids for both kinematic and Saybolt viscosities and for a range of temperatures. Charts available from ASTM Headquarters are:

- (a) Chart A. Saybolt Universal Viscosity: -30° to +450°F, 33 to 100,000,000 Saybolt Universal Seconds
- (b) Chart B. Saybolt Universal Viscosity, Abridged: -30° to +350°F, 33 to 100,000 Saybolt Universal Seconds
- (c) Chart C. Kinematic Viscosity, High Range: -30° to +450°F, 2 to 20,000,000 centistokes
- (d) Chart D. Kinematic Viscosity, Low Range: -30° to +450°F, 0.40 to 100 centistokes
- (e) Chart E. Kinematic Viscosity, Low Temperature Range: -100° to +450°F, 2.0 to 20,000,000 centistokes
- (f) Chart F. Kinematic Viscosity, Extended Range: -100° to +700°F, 0.40 to 20,000,000 centistokes

(2) Calculation of Viscosity Index

Test Methods: Federal Test Method 9111.2 (Ref. 17)
ASTM D-2270-64 (Ref. 16)

These methods provide tables and equations for calculating the *V.I.* of petroleum products from their viscosities at 100° and 210°F. Tables are provided for liquids with viscosities at 210°F between the values of 210 and 75.0 cSt.

Tedious calculation of *V.I.* can be eliminated by the use of data in ASTM Data Series 39a, *ASTM Viscosity Index Tables Calculated from Kinematic Viscosity*, September 1965. This reference gives *V.I.* in the following

ranges: from 0 to 200 *V.I.* for all liquids from 2 to 75 cSt at 210°F; up to 300 *V.I.* for liquids from 2.00 to 9.99 cSt at 210°F; and up to 250 *V.I.* for liquids from 10.00 to 19.98 cSt at 210°F.

3-2.3 VISCOSITY OF BLENDS OF TWO LIQUIDS

The ASTM viscosity-temperature charts can be used to predict the composition of a new blend of two liquids to give a required viscosity, or to estimate the composition of an existing blend when the viscosities of the two components are known. In this procedure, the vertical scale of any ASTM chart is used without change. The horizontal scale between 0°-100°F is relabeled 0-100 percent and used to represent the percent by volume of the higher viscosity component. The viscosity at a given temperature of the lower viscosity component is marked on the zero percent line and the viscosity at the same temperature of the higher viscosity component on the 100 percent line. The two points are connected by a straight line, and the required volumetric composition of any blend of intermediate viscosity may be read on the abscissa (see Fig. 3-16). Conversely, the composition of a blend can be estimated when the viscosities of the two components are known and plotted in this manner (Ref. 4).

3-2.4 VISCOSITY-PRESSURE PROPERTIES

The viscosity of a liquid varies with pressure as well as temperature. For many years pressure effects in hydraulic systems were neglected since the pressures encountered were moderate and the viscosity was not greatly affected. Viscosity increases with increases in pressure, and the rate of increase is greater at lower temperatures and pressures. The rate of increase is also influenced by the structural and chemical composition of the fluid. Graphs of viscosity vs pressure at several temperatures for a typical petroleum fluid are shown in Fig. 3-17. Graphs of viscosity vs temperature at several pressures for a typical synthetic fluid are shown in Fig. 3-18.

Most of the work on viscosity-pressure effects has been done in studies concerned with lubrication theory. Lubricating fluids for ball bearings and gears are often subjected to extremely high pressures at contact surfaces under which their viscosities are increased appreciably. At pressures as low as a few thousand pounds

per square inch, the increase in viscosity can cause considerable differences in the results obtained by a lubrication theory calculation (Ref. 4).

A number of empirical equations have been suggested for relating viscosity to pressure. The following one, although valid only over a moderate pressure range, is the one most commonly used (Ref. 20):

$$\eta_p = \eta e^{kp} \quad (3-20)$$

where

- η_p = absolute viscosity at pressure p , cSt
- η = absolute viscosity at atmospheric pressure, cSt
- e = 2.71828 (base of natural logarithms)
- k = a constant for a given oil and temperature, (psi)⁻¹
- p = pressure, psi

Several general statements about the viscosity-pressure properties of petroleum products can be made, namely:

(1) A pressure increase of about 500 psi has the equivalent but opposite effect on viscosity as a temperature increase of 2°F.

(2) The same increase in pressure will show a greater effect on viscosity at high pressures than at low pressures.

(3) Lower viscosity fluids are less affected by pressure than higher viscosity fluids.

(4) An increase in pressure will increase the *V.I.*

The study of the effects of pressure on viscosity is an area of research that has received considerable interest in recent years. The viscosity of liquids at pressures up to 150,000 psi and temperatures up to 425°F has been reported by the ASME (Ref. 21) and, more recently, by Wilson (Ref. 22). Klaus et al. (Refs. 23-25) have conducted viscosity-pressure studies on numerous liquids, at pressures up to 10,000 psi, which are likely to be encountered in typical hydraulic systems. As more data are accumulated on viscosity-pressure effects, more intelligent choices of lubricants and hydraulic fluids will be possible. The inclusion of viscosity-pressure data in design studies could result in the use of liquids of lower viscosity than the classical lubrication equations would indicate. Using a liquid of lower viscosity has the advantage of permitting lower operating temperatures, less liquid friction, and smaller power losses.

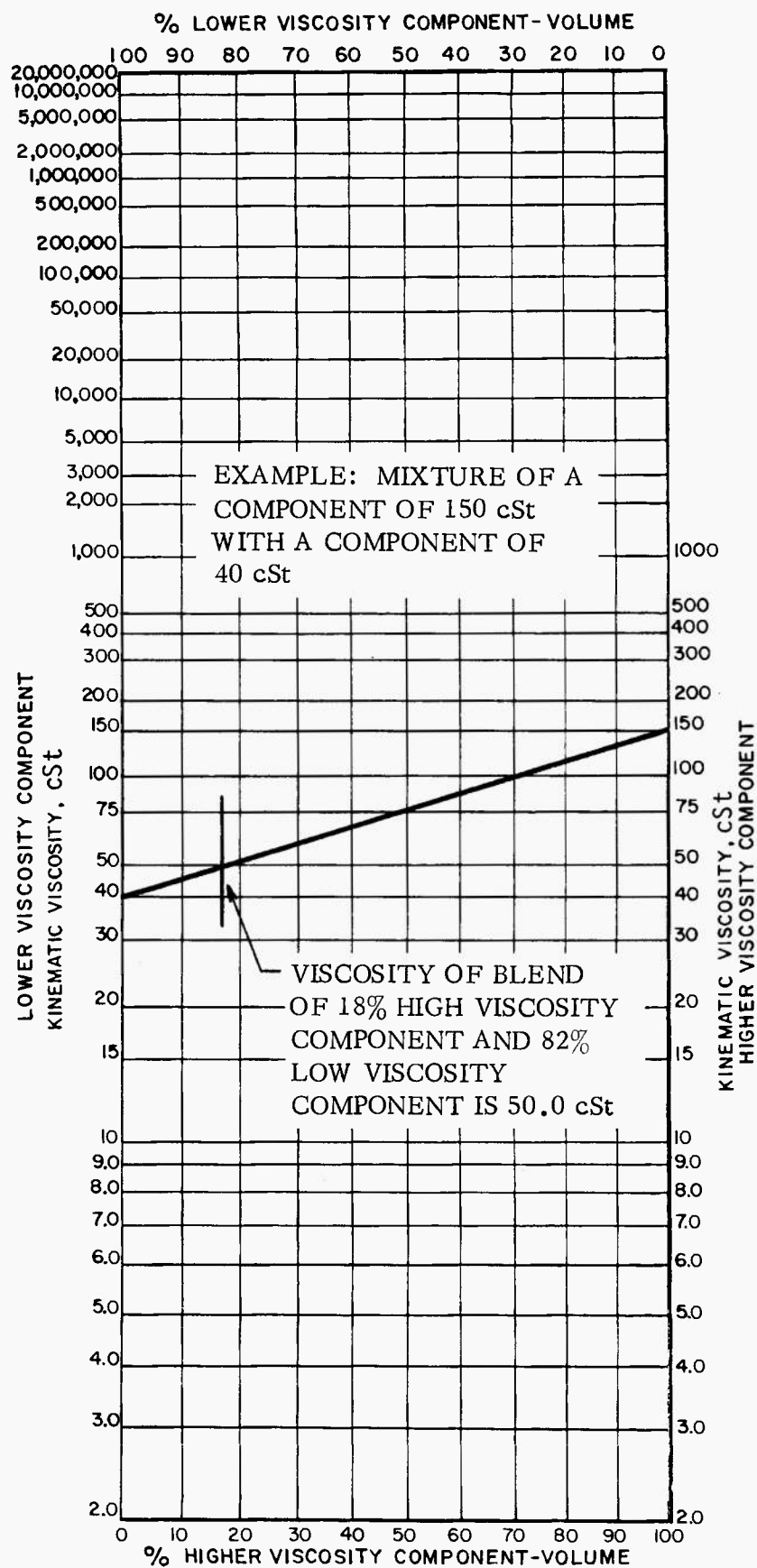


Fig. 3-16. Viscosity Blending Chart

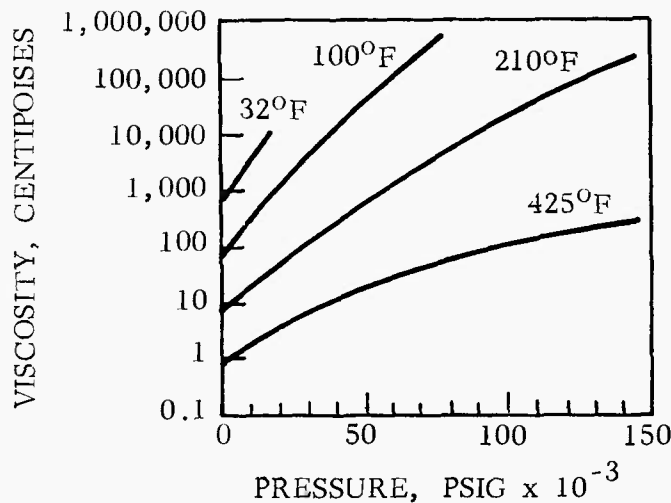


Fig. 3-17. Viscosity vs Pressure at Several Temperatures for a Typical Petroleum Fluid

[From: *ASME Pressure-Viscosity Report*, Vol. 2²¹. Used by permission of ASME]

3-2.5 VISCOSITY-SHEAR CHARACTERISTICS

Some aircraft and many industrial hydraulic fluids currently in use contain polymeric thickeners called Viscosity Index improvers, or "V.I. improvers", to reduce viscosity change due to temperature. When liquids containing these V.I. improvers are subjected to high rates of shear, they often suffer a loss in viscosity and V.I. because of degradation of the polymers. The unit of shear rate is the reciprocal second (sec^{-1}). A shear rate of one reciprocal second occurs when parallel planes 1 cm apart move in opposite directions at a relative speed of 1 cm/sec. High shear rates will occur

where speeds are high and clearances small. Some typical shear rates are shown in Table 3-2 (Ref. 26). Circulation of a hydraulic fluid through a system subjects the fluid to rapid shear rates and sudden pressure changes as it passes through orifices and close tolerance areas (Ref. 27). The resultant loss in viscosity may be either a permanent loss, or a temporary loss, or a combination of the two.

3-2.5.1 Temporary Viscosity Loss Due to Shear

Temporary viscosity loss is due to orientation or "lining-up" of the long chain polymer molecules in the direction of flow. The polymer molecules thicken a liquid more when they are oriented in a random manner, than when they are oriented in the direction of flow. The orientation of the molecules can actually be seen when the flow in transparent tubes is observed under polarized light (Ref. 28). When the shearing stress is removed, the liquids regain their original viscosity.

Temporary loss of viscosity has two important effects on the performance of hydraulic fluids—an increase in leakage and a reduction of fluid friction. Leakage around close fitting parts increases as the viscosity decreases and can result in reduced system efficiency if the rate becomes too great. However, the reduction in fluid friction that accompanies reduced viscosity increases system efficiency and performance. Several methods for measuring the temporary viscosity decrease have been developed. One method uses a bank of capillary tubes; another uses a rotating tapered plug viscometer. The concentric cylinder is another common apparatus. Any one of these methods is sufficient for determining the relationship between viscosity and shear rate (Ref. 28).

TABLE 3-2.
ESTIMATED SHEAR RATES OF LUBRICANTS

Application	Radial Clearance Between Moving and Stationary Parts, in.	Relative Velocity of Parts	Shear Rate, sec^{-1}
Piston-cylinder clearance in automotive engine	0.001	200-400 in./sec	200,000 to 400,000
Plain journal bearing (2-in. diameter)	0.001 to 0.0001	1800 rpm	188,000 to 1,820,000
Ball-type hydraulic pump	0.0003	3500 rpm	3,000,000
Bosch piston-type Diesel fuel pump	0.00004	36 in./sec	900,000

[From: Klaus and Fenske, "Some Viscosity shear Characteristics of Lubricants", *Lubrication Engineering*²⁶. Used by permission of ASLE.]

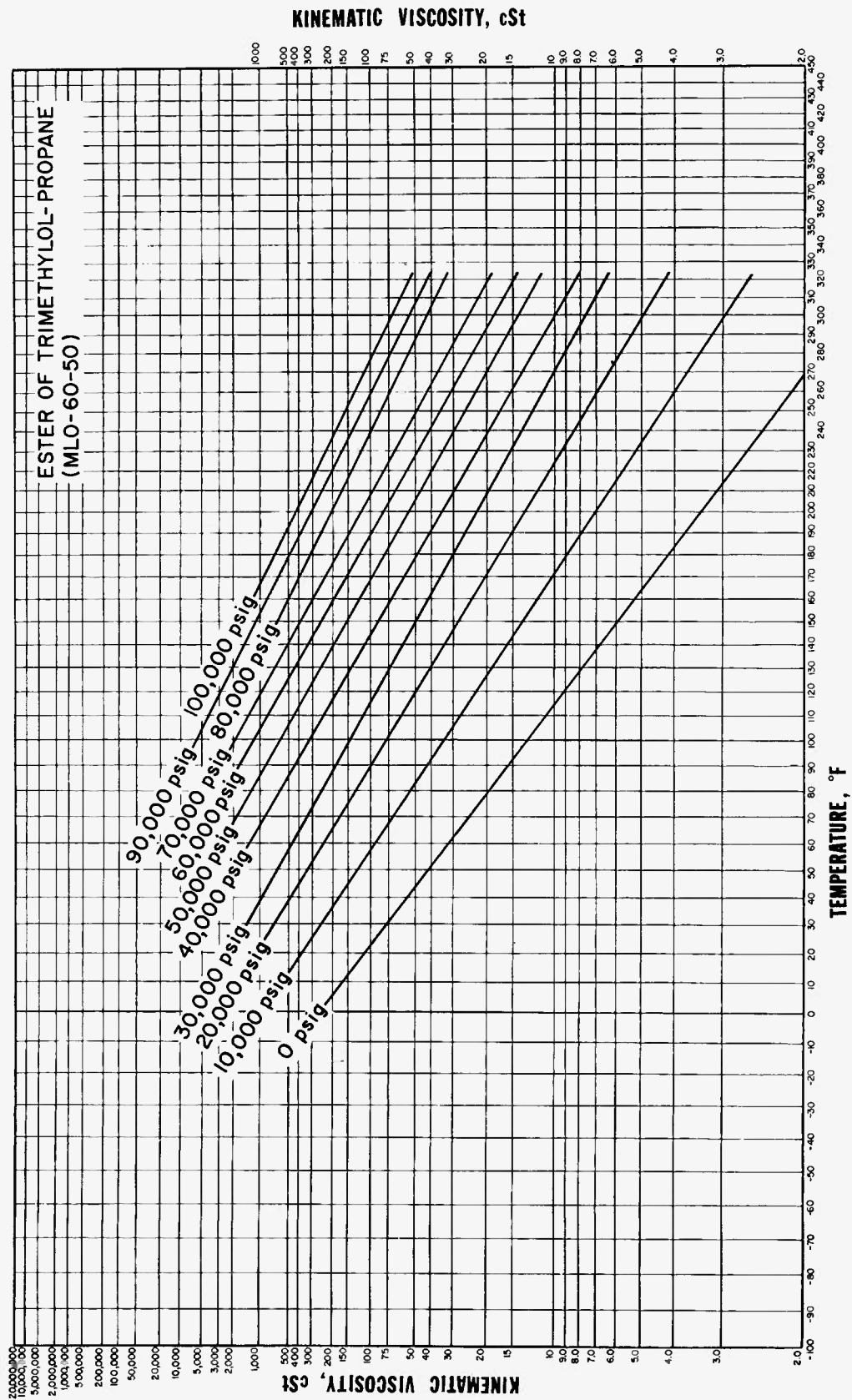


Fig. 3-18. Viscosity vs Temperature at Various Pressures for MLO-60-50 Fluid²²

3-2.5.2 Permanent Viscosity Loss Due to Shear

Permanent viscosity loss is the result of chemical breakdown or mechanical rupturing of the large polymer molecules into smaller molecules. Rupture of the polymer molecules may occur in both laminar and turbulent flow; however, polymer degradation is generally greater under turbulent conditions. Cavitation, where large shearing forces are developed by the rapid formation and collapse of cavities in the liquid, can cause extensive scission of the polymer chain. Polymer degradation by chemical reactions (oxidation, hydrolysis, radiation, etc.) does occur, but mechanical scission of the polymer chain resulting from the large shearing forces on the molecule is the principal cause of viscosity loss in hydraulic fluids. Viscosity losses due to reduction in the chain length (molecular weight) of the polymer thickener are permanent and the liquids do not regain their viscosity when the shearing forces are removed.

3-2.5.3 Test Methods for Viscosity-shear Characteristics

There are several methods of measuring permanent shear viscosity loss. Most of them are summarized in ASTM Special Technical Publication No. 182 (Ref. 29). The three most commonly used methods are the pump-orifice test, the sonic method, and the diesel injector method.

(1) *Pump-orifice Test*: The liquid is pressurized with a pump and the pressure is released by passing the liquid through a small orifice to a low pressure area. After a given number of cycles the amount of permanent shear viscosity loss is expressed as the percent change in the viscosity at a given temperature. This test simulates actual service conditions and employs hydraulic system components.

Federal Test Method 3471.2 (Ref. 30) describes a procedure and apparatus (see Fig. 3-19) used to determine shear stability of hydraulic fluids with a pump test. The method consists of pumping one pint of liquid through a simulated hydraulic system and reporting changes in visual appearance, viscosity, and neutralization number. Graphs of viscosity loss of MIL-H-5606B fluid during a pump loop test similar to that described above are shown in Fig. 3-20 (Ref. 31).

(2) *Sonic Method*: The sonic method consists of subjecting the liquid to high-frequency vibrations that produce permanent shear breakdown of the polymer

molecules in extremely short periods of time as compared to the pump tests. The sonic energy is supplied from magnetostrictive oscillators. One such device generates 10 kilocycles per second at 200 watts (Ref. 27). The sonic method has the advantages of using only a small sample (50 ml or less) of the liquid and requiring one hour or less to perform. Fig. 3-21 (Ref. 31) shows the effect of sonic irradiation on the viscosity of a typical MIL-H-5606B fluid.

The correlation between sonic results and pump test results has been poor in many cases. Recent investigations have shown that the poor correlation might be attributed to at least two factors (Ref. 32): (1) the sonic procedure is performed at atmospheric pressure whereas the pump test uses a reservoir under pressure, and (2) both methods vary in their effect on different polymers. The problem of dissolving gases in the liquid from the pressurized reservoir can be reduced by using an interface such as a diaphragm between the liquid and the pressurizing gas. When the effect of dissolved gases and the selective nature of the sonic irradiations are considered, there is closer correlation to data from pump tests. Considerable effort has been expended in developing a set of conditions to be used in the sonic method and much of the work has been summarized in ASTM Special Technical Publication No.182 (Ref.29).

(3) *Diesel Injector Method*: The diesel injector method is similar to the pump-orifice method in that the liquid is pressurized and forced through a small orifice. In the injector method, the diesel injector serves as both the pressurizing pump and the orifice. Excellent agreement between pump tests and results obtained by multiple passes through the diesel injector have been obtained (Ref. 4).

3-2.6 LOW-TEMPERATURE PROPERTIES

As hydraulic fluids are cooled, they become more viscous and flow becomes slower. If cooling is carried to sufficiently low temperatures, the fluids approach plastic solids. Many liquids, if cooled under prescribed conditions, will begin to precipitate wax or separate components at a specific temperature. This temperature is called the cloud point. If cooling under prescribed conditions is continued, a temperature will be reached at which the oil will not pour or flow. This temperature is defined as the solid point. By definition, the pour point is 5°F above the solid point. The pour point approximates the lowest temperature at which a liquid will flow in a container of a given size. To be useful, a hydraulic fluid must have a pour point below

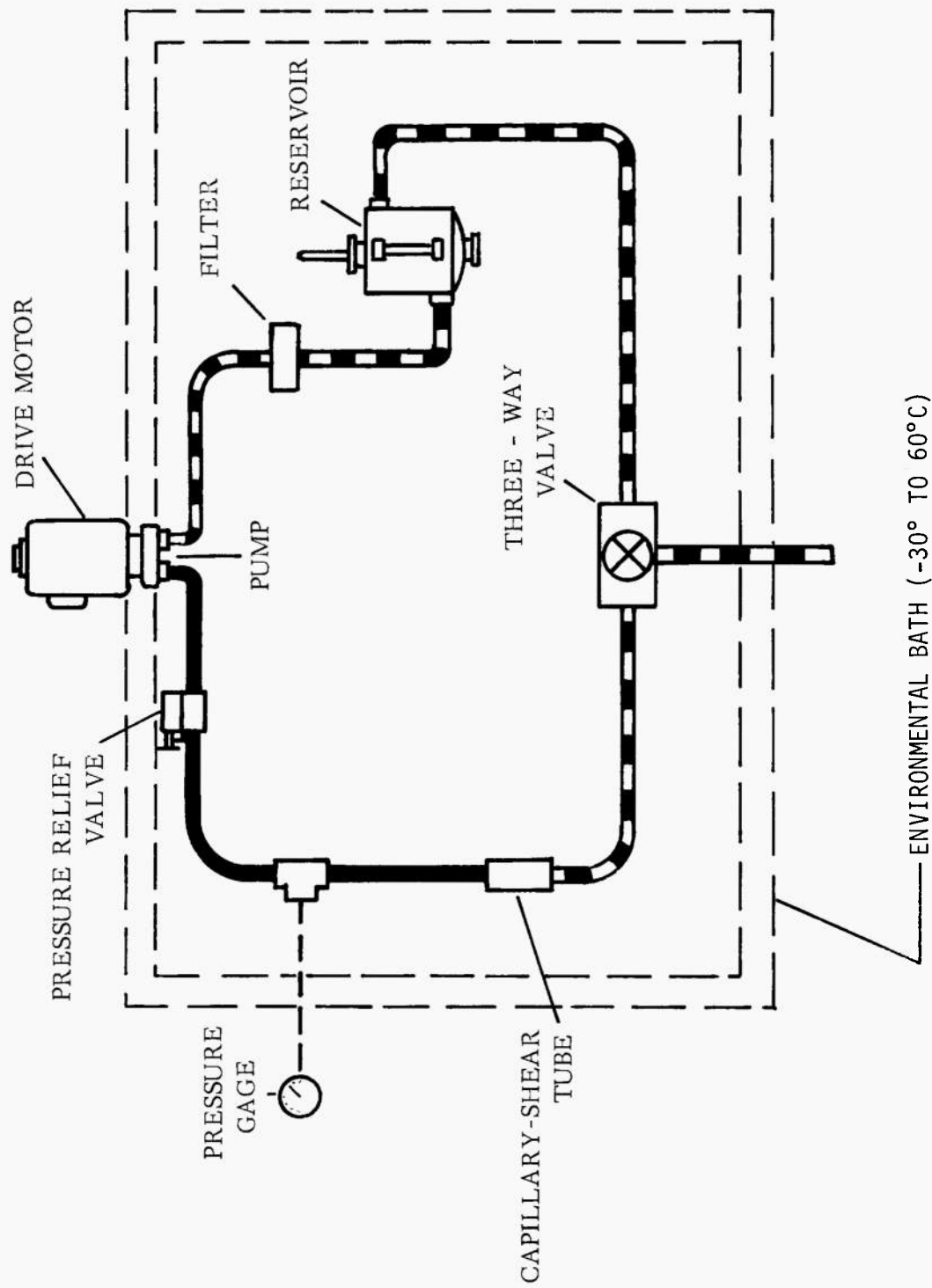


Fig. 3-19. Schematic Diagram of Pump Test Apparatus for Determining Shear Stability of Hydraulic Fluids³⁰

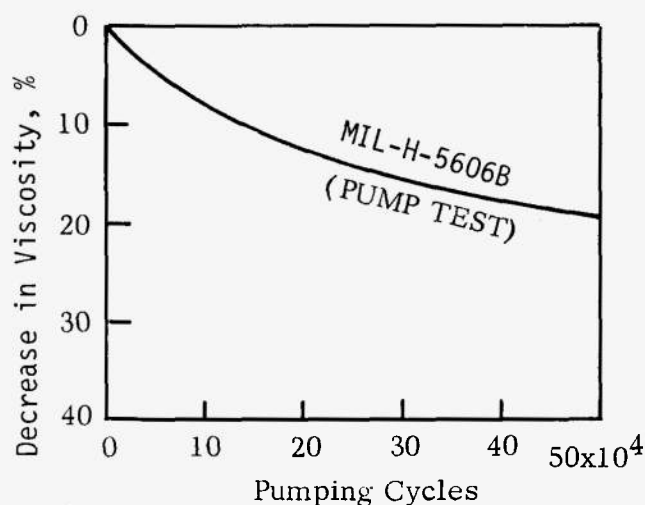


Fig. 3-20. Effect of Shear Upon Viscosity of a MIL-H-5606B Hydraulic Fluid in a Pump Test³⁰

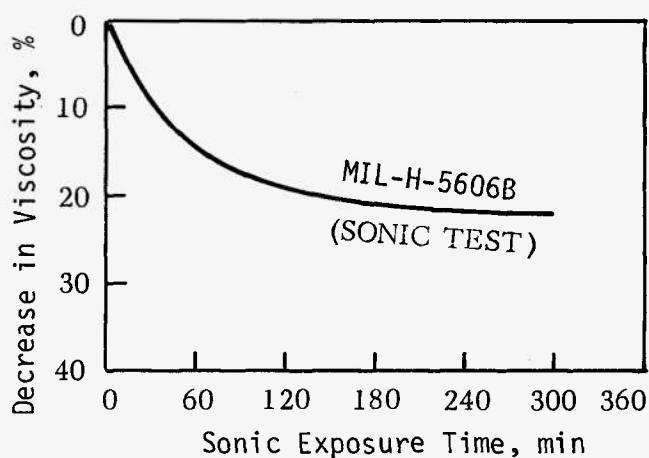


Fig. 3-21. Effect of Sonic Irradiation on the Viscosity of a MIL-H-5606B Hydraulic Fluid³⁰

the minimum temperatures expected in operation. It is difficult to define either pour point or solid point precisely as the transition from liquid to solid is gradual.

3-2.6.1 Cloud Point

The cloud point is of interest for use at low temperatures. It is defined as the temperature at which wax or other dissolved solids begin to crystallize and become noticeable when liquids are chilled under specified conditions. Dissolved moisture can also cause clouding of a liquid on cooling and lead to erroneous results. Many liquids have no cloud point. Some base stocks have no waxy components and other stocks can have the waxy

components removed. The latter are referred to as deep dewaxed fluids.

3-2.6.2 Pour Point

The pour point may mark a temperature at which crystallization of wax has proceeded to such an extent that further lowering of temperature would cause flow to cease (waxy pour point) or it may, with wax-free fluids, represent the temperature at which the viscosity is sufficiently high that further cooling would cause flow to cease (viscous pour point). Liquids which are free of wax or other components that can precipitate on cooling behave like Newtonian fluids even at low temperatures. The viscosity at the pour point is approximately the same for all fluids of this type and has been found to be in the range of 10^5 to 10^6 cSt.

Most commercially available petroleum fluids have a waxy pour point rather than a viscous pour point. They are Newtonian fluids only when the temperature is above the point at which wax begins to separate. The formation of waxy crystals does not mean the fluid has solidified. Flow has been prevented by the crystals but if the liquid is agitated to rupture the crystal structure, the liquid will flow even though the temperature is below the pour point. The waxy pour point is dependent upon such factors as the rate of cooling and degree of agitation (Ref. 4). Table 3-3 lists the minimum pour point required by four common Military Specifications for hydraulic fluids.

3-2.6.3 Freezing Point

For pure, or essentially pure, hydrocarbons the temperature at which solidification occurs is called the freezing point. This term is also frequently and loosely used for other petroleum products where the proper term would be either the cloud point, the pour point, or the solid point. The freezing point is defined as the temperature at which a pure hydrocarbon passes from a liquid to a solid state. Test methods for determining freezing points usually apply to fuels, solvents, and other types of relatively pure hydrocarbons.

3-2.6.4 Test Methods for Low Temperature Properties

(1) Cloud and Pour Point

Test Methods: Federal Test Method 201.8 (Ref. 33)
ASTM D-97-66 (Ref. 34)
ASTM D-2500-66 (Ref. 35)

TABLE 3-3.
POUR POINT REQUIREMENTS OF FOUR MILITARY SPECIFICATION FLUIDS

Specification	Fluid Type	Use	Pour Point, °F, max
MIL-H-5606B	Petroleum	Aircraft	-75
MIL-H-8446B	Nonpetroleum	Aircraft	-75
MIL-H-13866B	Petroleum	Artillery	-50
MIL-H-27601A	Nonpetroleum	Aircraft	-65

These methods describe the procedures for determining the cloud point for liquids which are transparent in layers 1-1/2 in. in thickness and for determining pour point for any petroleum fluid.

- (a) *Cloud point:* (ASTM D-2500-66, Federal Test Method 201.8) A sample of the fluid is placed in a test jar, heated at least 25°F above the approximate cloud point, and then chilled in successively cooler baths. At intervals of 2°F the sample is inspected for clouding. When a distinct cloudiness or haze appears at the bottom of the test jar, the temperature reading is recorded as the cloud point.

Precision: Duplicate results from one laboratory may differ by 4°F and the results of two different labs may differ by 8°F for gas oils. For all other oils, results of duplicate tests should not differ by more than 10°F.

- (b) *Pour point:* (ASTM D-97-66, Federal Test Method 201.8) A sample of the fluid is placed in a test jar of 1-1/4 in. diameter and heated to 15°F above the expected pour point, but not hotter than 115°F. The sample is then chilled in successively cooler baths. At intervals of 5°F, the jar is tilted and the fluid surface is inspected for movement. When the fluid reaches a temperature where the jar can be tilted horizontally for 5 sec with no movement, the temperature is recorded as the solid point. The pour point is taken as the temperature 5°F above the solid point temperature.

Precision: Results of the pour point from one laboratory may vary by 5°F and from different laboratories by 10°F.

(2) *Pour Stability Characteristics*

Test Method: Federal Test Method 203 (Ref. 36)

This method is used for determining the stable pour point of blends of winter grade motor oil and of certain types of hydraulic fluids.

A sample of the oil is placed in a glass jar in a bath and subjected to a schedule of temperature variations for a period of up to 6 days. The lowest temperature at which no surface movement will occur when the sample is turned horizontally for 3 sec (the solid point) is then determined. The stable pour point is recorded as the temperature 5°F above the solid point. This method differs from the method of par. 3-2.6.4(1) in that the sample first undergoes a period of heating and cooling over a period of several days.

Precision:

- (a) *Repeatability.* Results may vary in one laboratory by 5°F for oils with pour stability characteristics. For blends with solid points below 0°F results may vary 10°F.
- (b) *Reproducibility.* Results may vary in different laboratories by 10°F. The averages of three or more results per laboratory in different laboratories should not differ more than 5°F.

(3) *Diluted Pour Point*

Test Method: Federal Test Method 204 (Ref. 37)

This method is used for indicating the flow characteristics of engine oils that have been diluted with aviation gasoline.

A sample of the oil is diluted to a mixture of 70 percent oil and 30 percent diluent. The diluent is a mixture of 80 percent naphtha and 20 percent xylene. The pour point is determined as outlined in ASTM D-97-66 (Ref. 34) or Federal Test Method 201.8 (Ref. 33) for cloud and pour point (par. 3-2.6.4(1)).

Precision: The same limits as set forth in ASTM or Federal Test Method for cloud and pour point (par. 3-2.6.4(1)) apply to this method.

(4) *Cloud Intensity at Low Temperature*

Test Method: Federal Test Method 202 (Ref. 38)

This method describes the procedure for determining the ability of hydraulic fluids or highly refined light lubricating oils to remain free of turbidity at low temperatures.

A sample of the fluid and a standard are stored at -65°F (or lower as specified by the purchaser) for a

specified period. It is then agitated and its turbidity is compared to the standard. The standard is a mixture of barium chloride, sulfuric acid, and sodium hydroxide. The turbidity of the sample is reported as less than, more than, or equal to the standard.

3-2.6.5 Significance of Cloud and Pour Points

Many hydraulic systems are required to operate in extremely cold weather. Under these conditions the oil must flow to the suction side of the hydraulic pump on start-up of the system. The pour point, being the lowest temperature at which a liquid will flow under normal gravity head, must be considered in selecting a hydraulic fluid for cold weather applications. The oil chosen for the system should have a pour point below the lowest anticipated start-up temperature.

The cloud point, on the other hand, is of little significance. A formation of the waxy crystals may tend to plug up small orifices, but this fact is taken into account in the design of hydraulic systems for low temperature operation. The clouding of liquids, however, will sometimes cause the clogging of filters if no preheating facilities are available.

3-2.7 FLAMMABILITY CHARACTERISTICS

The measurement of the flammability characteristics of a hydraulic fluid is complex. The degree of flammability is influenced by the characteristics of the liquid, the source of the ignition, whether the liquid has vaporized, and many other factors. The potential danger from hydraulic fluids is frequently great because of the high pressures involved in many systems. Fracture of hydraulic lines or leakage from faulty connections can form a fine spray of liquid which is readily ignitable. Numerous tests have been developed to determine the flammability characteristics of liquids both under laboratory conditions and also under simulated operating conditions.

3-2.7.1 Flash and Fire Points

The flash and fire points are the most common laboratory measurements of the flammability of a liquid. The flash point is the minimum temperature at which sufficient liquid is vaporized under specified conditions to create a mixture that will burn if ignited. As the name "flash" indicates, burning at this point is only

an instantaneous flash. The fire point, however, is the minimum temperature at which sufficient vapor is continuously generated to sustain combustion. Since differences between flash and fire points are not great, and since fire point data cannot be obtained in a closed tester, the fire point is often omitted in commercial data on hydraulic fluids. Table 3-4 lists the flash point requirements of five common Military Specifications for hydraulic fluids.

3-2.7.1.1 Test Methods for Flash and Fire Points

(1) *Cleveland Open Cup Method*

Test Methods: Federal Test Method 1103.6 (Ref. 39)
ASTM D-92-66 (Ref. 40)

These methods describe a procedure for determining the flash and fire points of petroleum products except fuel oils and those products having an open cup flash point below 175°F.

The test cup is filled with the sample and the temperature of the sample is increased, first rapidly and then at a slower constant rate as the flash point is approached. At 5°F intervals, a small flame is passed across the cup in a prescribed manner. The lowest temperature at which application of the test flame causes vapors above the surface of the sample to ignite is taken as the flash point. The test is continued until the application of the test flame causes the fluid to ignite and burn for at least 5 sec. That temperature is the fire point. A sketch of the Cleveland Open Cup apparatus is shown in Fig. 3-22.

Precision: Results should not be considered suspect unless they differ by more than the following amounts:

(a) Repeatability.

Flash point 15°F, 8.3°C

Fire point 10°F, 5.5°C

(b) Reproducibility.

Flash point 30°F, 16.7°C

Fire point 20°F, 11.1°C

(2) *Tag Closed Cup Tester Method*

Test Methods: Federal Test Method 1101.6 (Ref. 41)
ASTM D-56-64 (Ref. 42)

These methods describe procedures for determining the flash and fire points of fluids that flash below 175°F, with the exception of products classified as fuel oils.

The sample is placed in the cup of the tester; the lid is closed; and the temperature is increased at a slow constant rate. A small flame is directed into the cup at 1°F intervals. The lowest temperature at which the application of the test flame causes a vapor above the sample to ignite is the flash point.

TABLE 3-4.
FLASH POINT REQUIREMENT OF FIVE MILITARY SPECIFICATION FLUIDS

Specification	Fluid Type	Use	Flash Point, °F, min
MIL-H-5606B	Petroleum	Aircraft	200
MIL-H-8446B	Nonpetroleum	Aircraft	395
MIL-H-13866B	Petroleum	Artillery	210
VV-B-680a	Nonpetroleum	Automotive	179.6
MIL-H-27601A	Petroleum	Aircraft	360

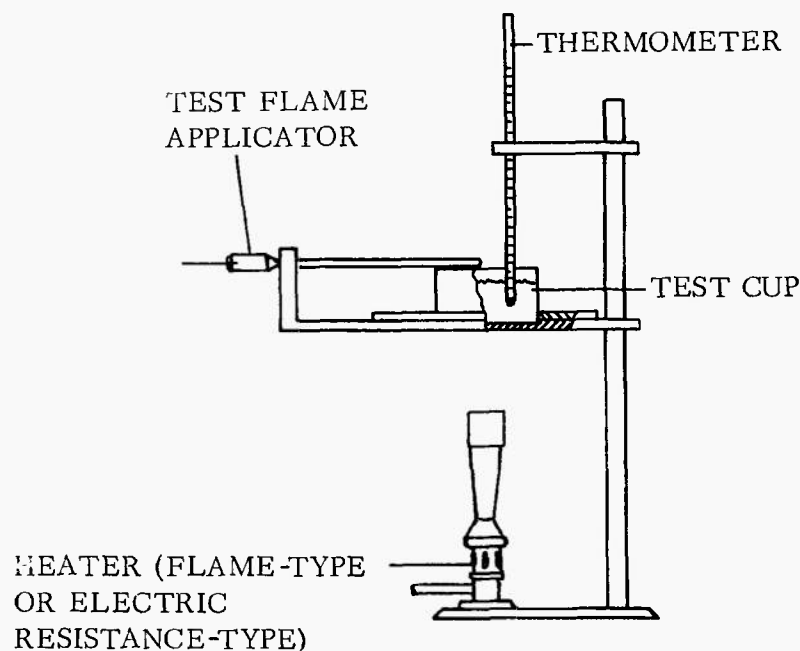


Fig. 3-22. Cleveland Open Cup Flash and Fire Point Test Apparatus

Precision: Results should not be considered suspect unless they differ by more than the following amounts:

- (a) Repeatability. 2°F
- (b) Reproducibility. Below 55°F–6°F
55°F or above–4°F
- (3) *Pensky-Martens Closed Cup Tester Method*
Test Methods: Federal Test Method 1102 (Ref. 43)
ASTM D-93-66 (Ref. 44)

These methods describe procedures for the determination of the flash point of fuel oils, lubricating oils, suspensions of solids, liquids that tend to form a surface film under test conditions, and other liquids, with the Pensky-Martens Closed Cup Tester.

The sample is placed in the cup of the tester; the lid closed; and the sample heated at a slow, constant rate with continual stirring. A small flame is directed into the cup at 5°F intervals with simultaneous interruption of stirring. The test flame is applied by operating the

mechanism on the cover that opens a shutter, lowers the test flame through the opening into the vapor space of the cup in 0.5 sec, leaves the flame in place for 1 sec, and quickly retracts the flame and closes the shutter. The flash point is recorded as the temperature of the sample at the time the test flame application causes a distinct flash in the interior of the cup.

Precision: Results should not be considered suspect unless they differ by more than the following amounts:

Material	Flash Point Range	Repeatability	Reproducibility
Suspension of Solids	95° to 110°F	4°F	6°F
All	Below 220°F	4°F	6°F
Others	Above 220°F	10°F	15°F

3-2.7.1.2 Significance of Flash and Fire Points

Petroleum liquids do not burn as such, but in general, must first be vaporized. The flash and fire points are measures of the minimum temperature at which sufficient vapor will be given off from the liquid so that a combustible mixture of air and vapor is obtained. In this manner, the relative fire and explosion hazard can be estimated from the flash and fire points.

Flash and fire points are also useful for evaluation of used liquids. If a liquid undergoes a rise in flash or fire point while in service, loss of the lighter fractions by evaporation is indicated. A lower flash or fire point is an indication that the liquid has become contaminated with a more volatile product (such as a fuel) or that some of the heavier fractions have broken down. The flash and fire points are also aids in establishing the identity of unknown petroleum products.

3-2.7.2 Flammability Tests Under Simulated Service Conditions

There are many complex factors involved in assessing the flammability of hydraulic fluids, and no one single test can be used to evaluate all of the types of liquids under all of the expected conditions of use. The flash and fire points are laboratory tests that bear little resemblance to actual operating conditions. As a result, several different methods for testing the flammability of liquids were developed. Most of these tests were designed to simulate conditions in aircraft resulting from a broken hydraulic line spraying liquid onto various sources of ignition. Although the tests were developed primarily for the aircraft industry, they are useful in any industry where hydraulic liquids are exposed to ignition sources. Three of the more common of these tests—the spray ignition, the hot manifold or hot surface ignition, and the incendiary gun fire test—are described in MIL-F-7100, *Fluid, Hydraulic, Nonflammable, Aircraft* (Ref. 45), an early specification for a fire-resistant hydraulic fluid. It was issued December 1950 and cancelled February 1958. No products were ever produced that conformed to the specification. The fire-resistance tests in the specification (described briefly here) are still used by many companies involved in hydraulic fluid work, although they vary from company to company.

Other tests are described in the literature, in various Military Specifications, and in ASTM special publications. Many of these tests are similar in nature but differ in their apparatus and procedures. A major problem confronting industry today is the lack of test standardization and interpretation of test results to adequately measure fire resistance of fluids. A review of

the general types of tests and procedures and the efforts towards standardization is given in Ref. 46.

(1) Spray Ignition Tests

There are two versions of this test—the high-pressure spray ignition test and the low-pressure spray ignition test.

(a) *High-pressure Spray Test (MIL-F-7100 (Ref. 45))*: The liquid is pressurized to 1,000 psi with nitrogen and forced through an orifice 0.0145 in. in diameter. Attempts are made to obtain ignition by application of an oxy-acetylene torch flame at various standard distances from the nozzle. At each position, a report is made as to whether or not the fluid will ignite, will flash with difficulty, or flashes readily. If flashing occurs, the distance from the orifice at which the ignition or flashing is carried downstream from the test flame area, and whether the flashing is self-extinguishing or results in a sustained fire, are also reported. A pictorial sketch of the high-pressure spray ignition test apparatus is shown in Fig. 3-23.

(b) *Low-pressure Spray Test (Ref. 4)*: A fire is started in a metal pan filled with oil-soaked rags and is allowed to burn. The liquid to be tested is sprayed towards the fire from the reservoir of an ordinary paint spray machine several feet from the fire. The increased intensity of the fire is then used as a measure of the flammability of the liquid. A pictorial sketch of the low-pressure spray ignition test apparatus is shown in Fig. 3-24.

An alternative low-pressure spray ignition test has been developed by Rowand and Sargent (Ref. 46). This method uses an airless paint spray gun. The gun generates a flat, well-defined atomized spray by pumping the liquid onto a high-speed rotating disk which propels the liquid in the form of small droplets through a slot in the side of the gun. A glass blower's torch 4 in. from the nozzle is the ignition source. The amount of flame produced in the spray is used as a measure of the flammability of the liquid. This method has the advantages of requiring only electricity, a source of ignition, and can be performed in a laboratory hood.

(2) Hot Manifold Ignition Test (MIL-F-7100 (Ref. 45))

The liquid is allowed to drop at a specified rate on a simulated aircraft manifold heated to approximately 1300°F. The ignition of the liquid and the carrying of the flame to the pan below the manifold are used as measures of the flammability of the liquid. Variations of the test involve raising or lowering the manifold

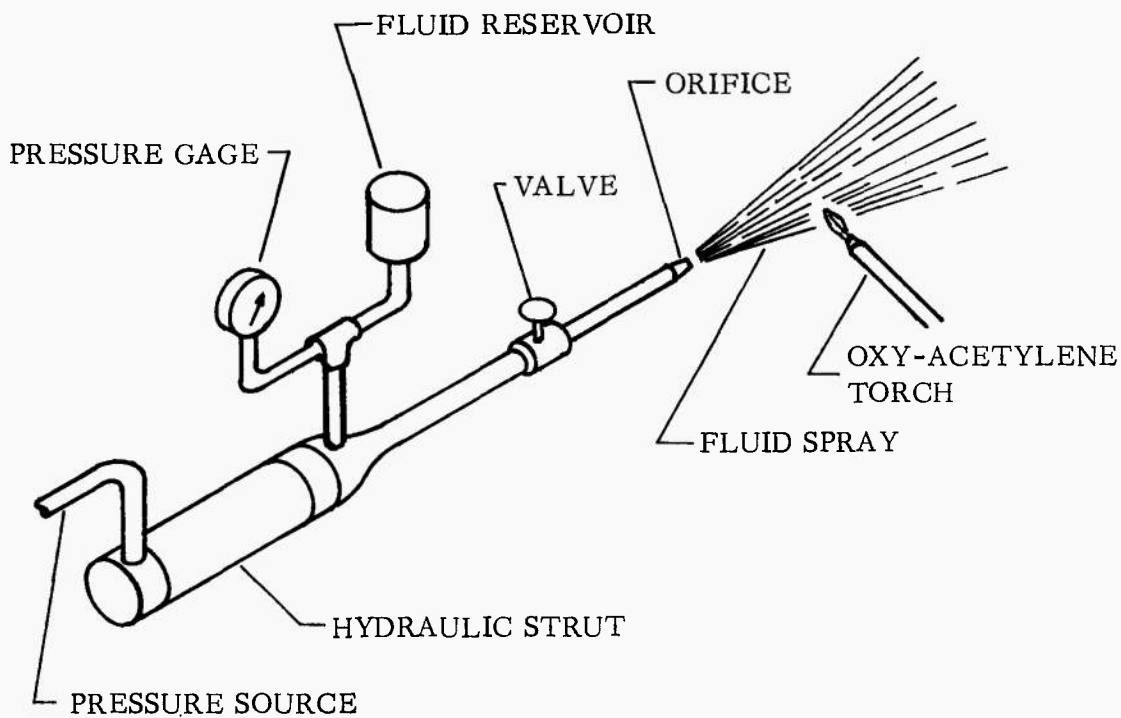


Fig. 3-23. High-pressure Spray Ignition Test Apparatus

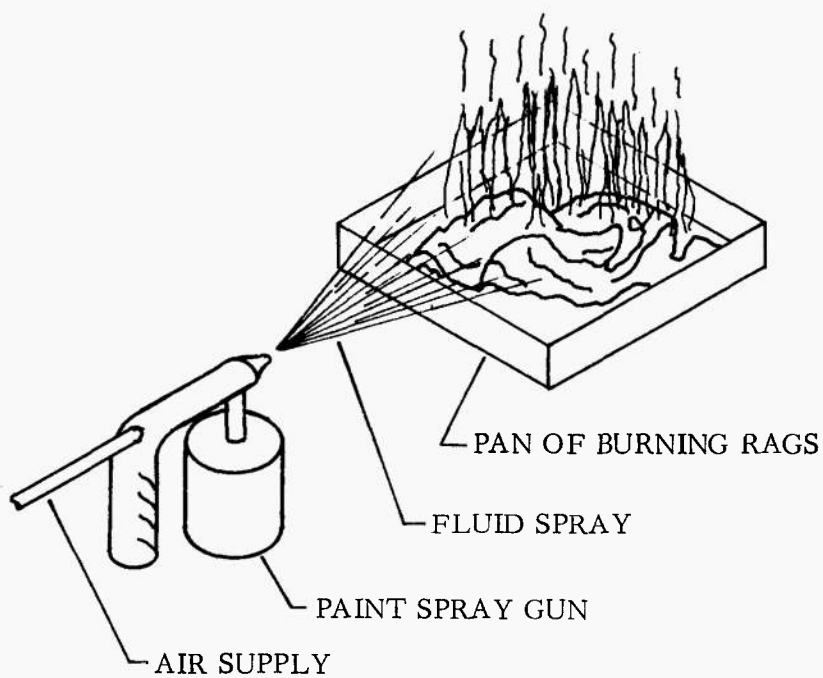


Fig. 3-24. Low-pressure Spray Ignition Test Apparatus

temperature until ignition occurs or until the limits of the apparatus have been exceeded. This variation provides an indication of the spontaneous ignition temperature of liquids contacting heated steel surfaces in the presence of large amounts of air. A pictorial sketch of the hot manifold spray ignition test apparatus is shown in Fig. 3-25.

(3) *Incendiary Gun Fire Tests* (MIL-F-7100 (Ref. 45))

The liquid is placed in a 3 ft long, 5/8 in. OD aluminum alloy tube and pressurized to 1,000 psi with nitrogen. A cal .30 incendiary bullet is fired from a range of 50 yd into the tube. Observations for burning or explosion of the liquid are made and are reported as a measure of the flammability of the liquid.

(4) *Compression Ignition*

It has been found that high-pressure air suddenly expanding into a confined space containing organic matter such as a hydraulic fluid can cause ignition

and/or explosion, depending on the rate of pressure release, volume of air, and quantity of organic material. The phenomenon of compression ignition can be important in generating fires in hydraulic systems. Accumulators, pressure gages, and other closed-end equipment are especially susceptible to this phenomenon. Two basic tests have been developed to determine the compression ignition characteristics of hydraulic fluids—the diesel engine test and the shock tube or piping system test.

(a) *Diesel Engine Compression Ignition:* This test is described in MIL-H-19475 (Ref. 47), a Military Specification for hydraulic fluids for Naval aircraft catapult launching systems. The test is a modification of the ASTM CFR Cetane rating engine test described in *ASTM Manual of Engine Test Methods for Rating Fuels*. A sample of the liquid is injected into a variable compression diesel engine, and the

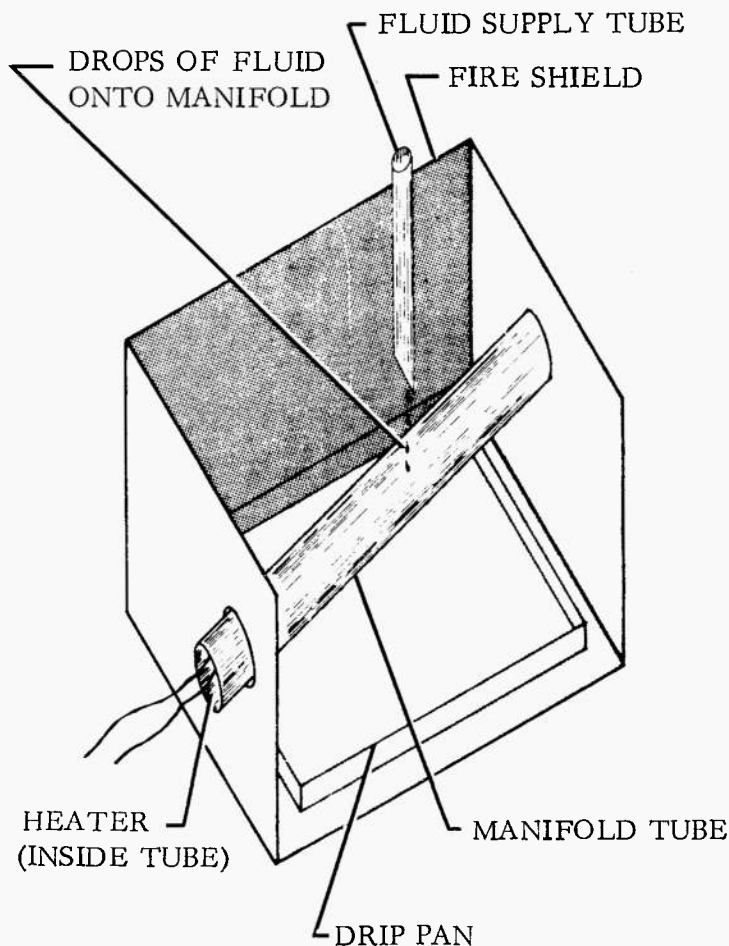


Fig. 3-25. Hot Manifold Ignition Test Apparatus

engine is then turned over at various compression ratios. The lowest compression ratio for combustion of the liquid is reported as a measure of the fluid's flammability. The higher the compression ratio, the more resistant the liquid is to compression ignition.

- (b) *Shock Tube or Piping System Test*: This test is described in MIL-H-22072 (Ref. 48) for a fire-resistant hydraulic fluid. A small amount of steel wool soaked with the liquid is placed at the closed end of a pipe. By use of high-pressure air and a fast opening valve, a shock wave is introduced and directed down the pipe. Combustion of the liquid on the steel wool can be determined by a rapid rise in temperature of the steel wool or by examination at the end of the test. Several repeat tests are conducted, and the results are reported as the ratio of the number of times that fire occurred to the number of tests tried at a given temperature. The fewer times the liquid burns, the more resistant it is to compression ignition. Reproducible results have been difficult to obtain in this test.

3-2.7.3 Effects of Evaporation on Flammability (Pipe Cleaner Test)

Test Method: Federal Test Method 352 (Ref. 49)

This method is used for determining the effect of evaporation on the flammability of a liquid petroleum product. A pipe cleaner, soaked with the fluid, is passed repeatedly through a flame at a rate of 25 cycles per minute and the number of passes required for ignition is noted. The fluid is then stored in an oven for the time and at the temperature required by the fluid specification, and its flammability is rechecked. Four repeats of the test are made before and after heating in the oven. The results are reported as the average number of cycles necessary for a self-sustaining flame to be achieved on the pipe cleaner both before and after partial evaporation in the oven. A sketch of the test apparatus is shown in Fig. 3-26.

3-2.7.4 Autoignition Temperature

The autoignition temperature (AIT)—often called the spontaneous ignition temperature (SIT)—is that temperature at which a flame can be obtained without an external source of ignition. It should not be confused with flash or fire points which rely upon ignition source. Autoignition temperature is determined by

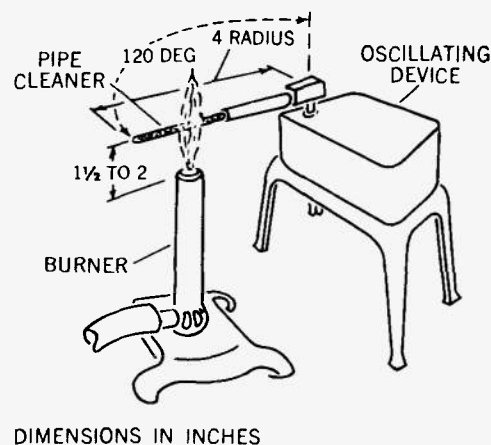


Fig. 3-26. Test Apparatus for the Pipe Cleaner Evaporation Test

ASTM D-2155-66 (Ref. 50). A small sample of the liquid to be tested is injected, with a hypodermic syringe, into a heated glass flask containing air. The contents of the flask are observed in a darkened room for 5 min following injection of the sample or until ignition occurs. Ignition is evidenced by the sudden appearance of a flame inside the flask. The lowest temperature at which autoignition occurs is taken as the autoignition temperature of the product in air at 1 atmosphere pressure. The time lag between injection and ignition is also reported. A cross-sectional sketch of the AIT apparatus is shown in Fig 3-27.

A new test procedure is expected to be included in the revised edition of Federal Test Method Standard 791a. The new procedure will be designated Method 5050 and entitled "Autogenous Ignition at Reduced or Elevated Pressure". The temperature determined with this test procedure is sometimes referred to as the reaction threshold temperature.

The autoignition temperature is a laboratory measurement and is very sensitive to the procedure used in its determination. It has been shown that in practice autoignition depends on many factors, such as the nature of the surface contacting the liquids, the composition of the combustible air mixture, and the pressure at the area of contact. Researchers at the U. S. Bureau of Mines (Ref. 51) have found that the AIT of a MIL-O-5606 liquid increases appreciably with a decrease in environmental pressure below one atmosphere but changes little with increasing environmental pressures above one atmosphere (Fig. 3-28). Not all liquids will have the marked change in slope of the AIT/pressure curve near atmospheric pressure shown on Fig. 3-28.

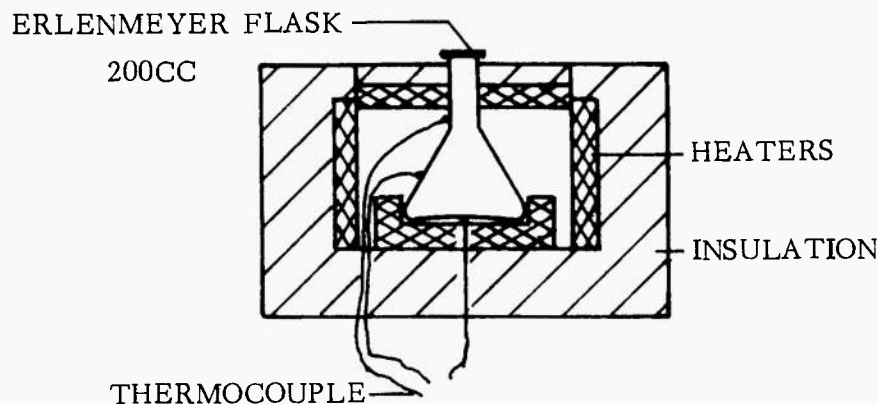


Fig. 3-27. Autoignition Temperature Test Apparatus

Some liquids will have a gradual decrease in minimum spontaneous ignition temperature with pressure increase and may or may not exhibit a slope change near one atmosphere. For example, Fig. 3-29 shows that the AIT of a chlorinated phenyl methyl silicone liquid is essentially a linear function of pressure. Figs. 3-28 and 3-29 also show that the nature and type of surface in contact with these liquids have little or no effect on the change in AIT with pressure. It has also been found (Ref. 52) that the AIT generally decreases with increasing environmental oxygen content (see Fig. 3-30).

3-2.7.5 Fire-resistant Liquids

The development of liquids that are inflammable or highly fire-resistant is the area of hydraulic fluid research that is receiving the greatest attention. As late as 1950 fire-resistant hydraulic fluids were uncommon. For reasons of safety, insurance companies and Government and industrial safety agencies have encouraged the use of fire-resistant fluids in Government, industrial, and agricultural equipment. Fire-resistant liquids should not be confused with high-temperature liquids. A fire-resistant liquid will not burn easily. A high-temperature liquid will not significantly change its properties at "high temperatures". Water is a fire-resistant liquid but it is not a high-temperature liquid.

One of the fundamental properties of petroleum liquids is their flammability. Although the flammability characteristics of petroleum liquids can be modified by the use of special refining procedures (Ref. 50) and/or the use of additives, fluids of this type have shown considerable improvement in fire resistance over MIL-H-5606B type hydraulic fluids (Ref. 55). Other categories of fire-resistant liquids are synthetic, water base,

and emulsion-type. A complete discussion of the various types is beyond the scope of this text and the discussion here will be limited.

(1) *Synthetics*: A wide variety of synthetic liquids have been investigated as candidate hydraulic fluids, and certain types have been adopted and specifications written (see Chapter 4). Some of the typical classes of fluids under investigation are phosphate esters, halogenated hydrocarbons, silicones, and silicates. A detailed discussion of synthetic fluids can be found in Refs. 53, 54, and 55.

(2) *Water-glycol*: Water-glycol base fire-resistant liquids are solutions of from 35 to 50 percent water in ethylene or propylene glycol, which are thickened, if necessary, to a higher viscosity by adding a water-soluble polyglycol. The fire resistance of these liquids is due entirely to the presence of water. They were originally developed for use in military equipment but have been used extensively in industrial equipment.

(3) *Emulsions*: Emulsion-type hydraulic fluids are multiphase systems containing two liquids, such as oil and water, which are not usually mutually soluble. Water-in-oil emulsions have found wide acceptance as industrial hydraulic fluids. The emulsions contain up to 40 percent water which acts as a snuffer to render the liquid fire-resistant.

3-2.8 VOLATILITY

All liquids tend to vaporize when they are heated. The volatility of a liquid describes the degree and rate at which it will vaporize under given conditions of

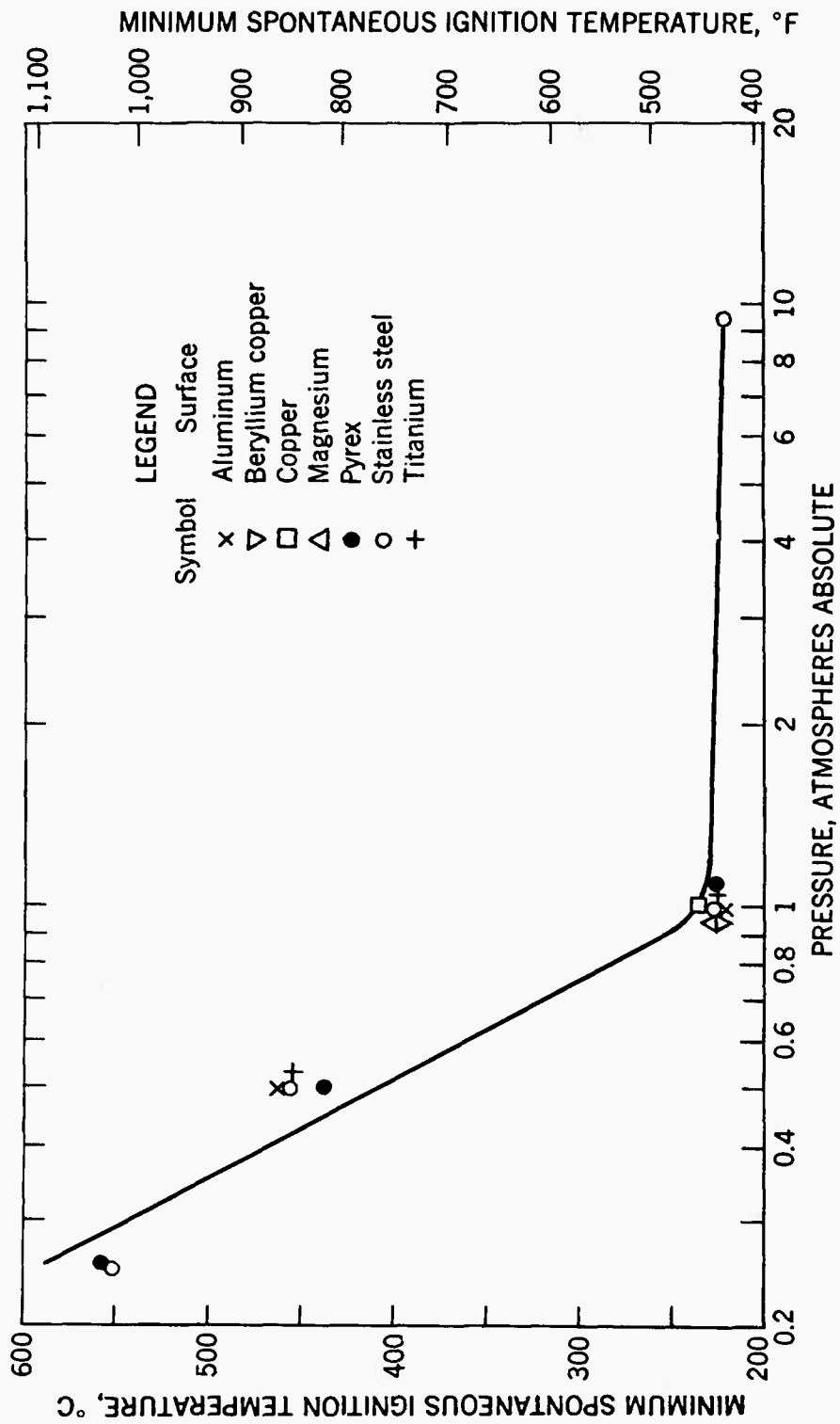


Fig. 3-28. Spontaneous Ignition Temperature of a MIL-O-5606 Fluid in Air in Contact With Various Surfaces As a Function of Test Chamber Pressure⁵¹

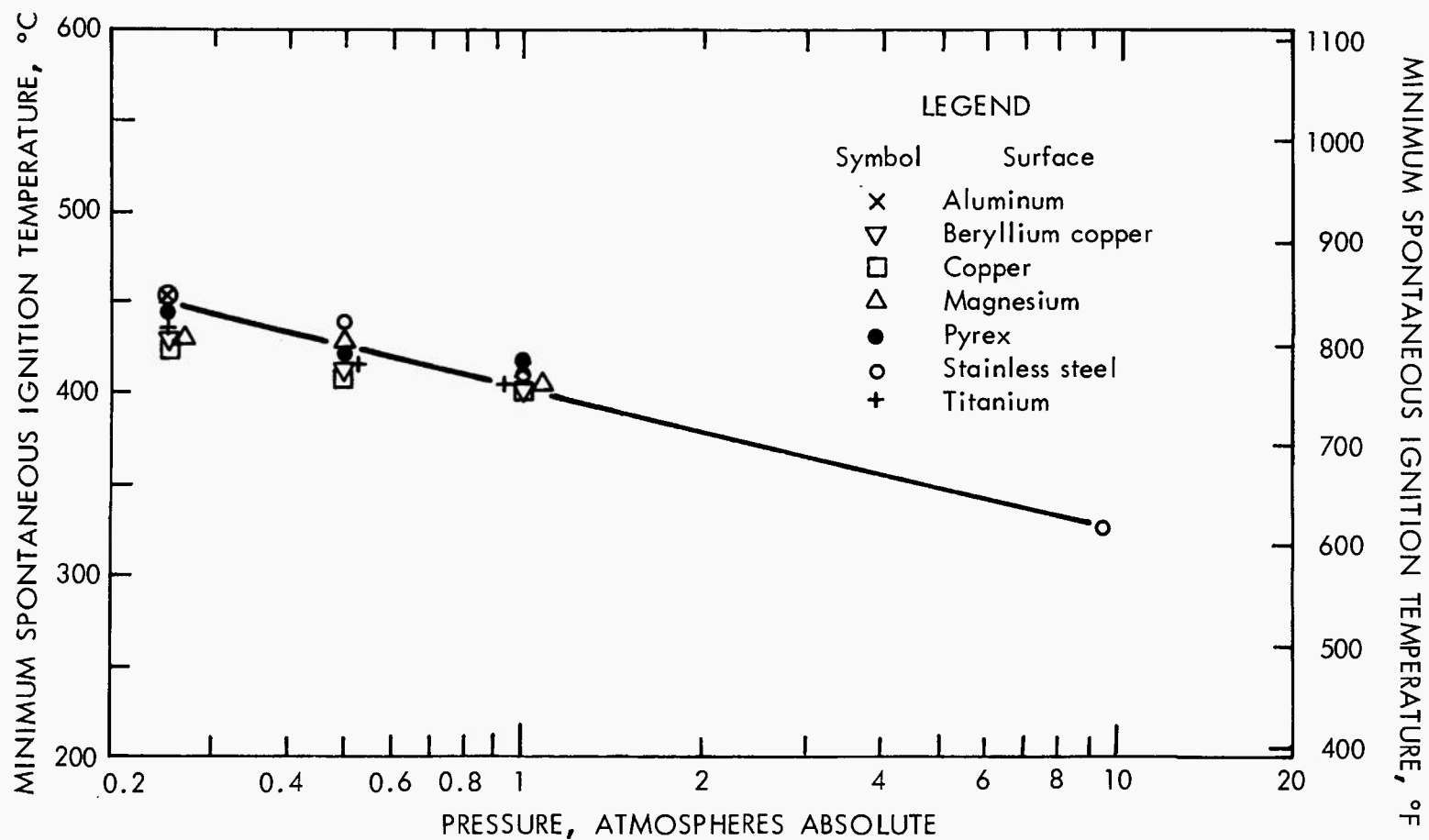


Fig. 3-29. Spontaneous Ignition Temperature of a Chlorinated Phenyl Methyl Silicone in Air in Contact With Various Surfaces As a Function of Test Chamber Pressure⁵¹

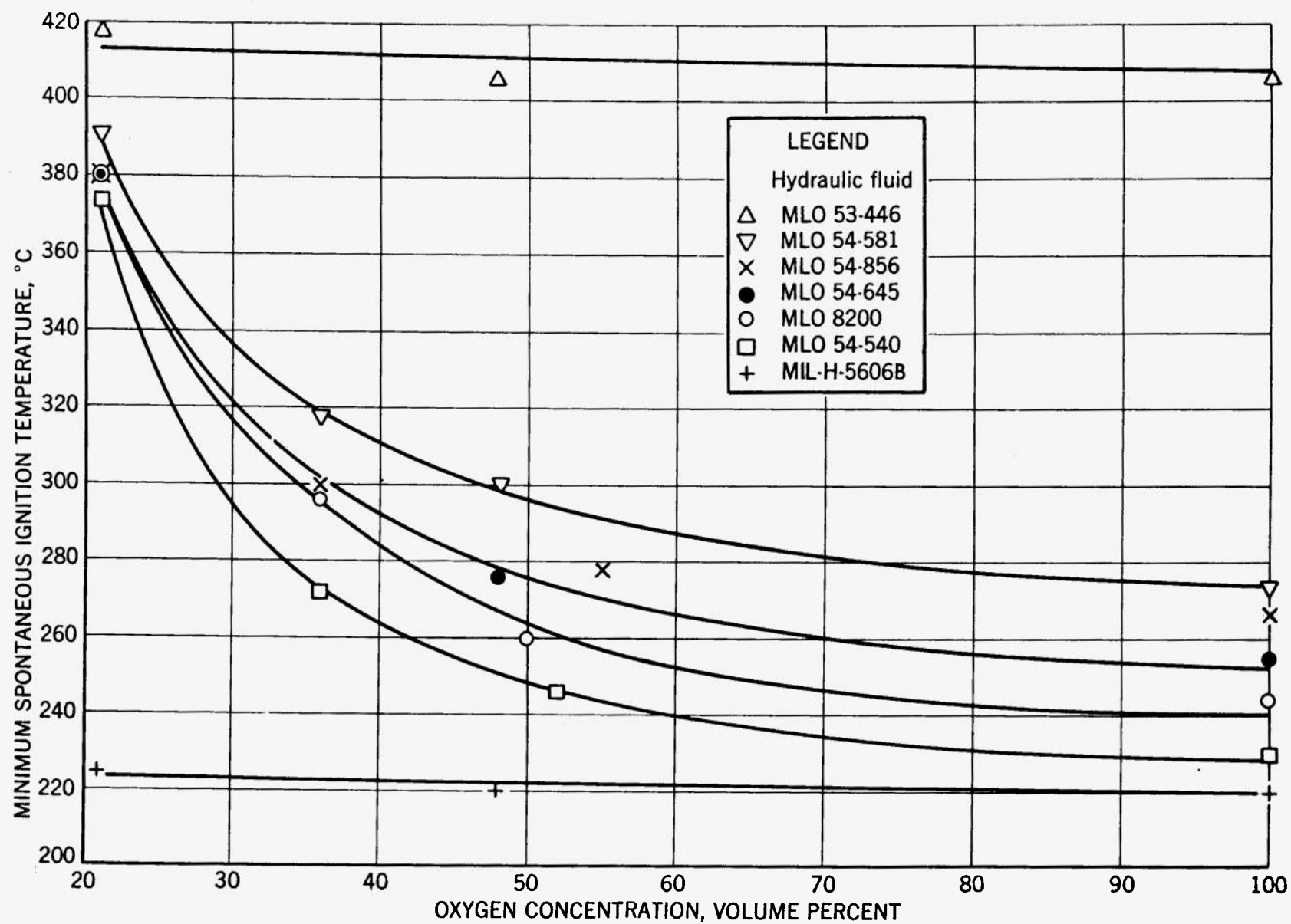


Fig. 3-30. Spontaneous Ignition Temperature of Seven Hydraulic Fluids at Atmospheric Pressure in Contact With a Pyrex Glass Surface As a Function of Oxygen Concentration⁵²

temperature and pressure. It is desirable that a hydraulic fluid have low volatility. Vaporization of a liquid in service can result in pump damage through cavitation and a reduction in efficiency. There are three characteristics generally used to indicate the volatility characteristics of a liquid—vapor pressure, boiling point, and evaporation loss. All three are different aspects of the volatility of a liquid.

3-2.8.1 Vapor Pressure

The pressure exerted by a vapor which is in equilibrium with the liquid is known as vapor pressure. For a given liquid, this pressure is a function only of temperature. The more volatile the liquid, the higher the vapor pressure at a specified temperature and the faster the vaporization.

The vapor pressure for a pure liquid is a physical property of the liquid for a given temperature. However, most hydraulic fluids are mixtures of several components. The vapor pressure of the mixture is a composite value that reflects the combined effects of the individual components. Theoretically, the vapor pressure of the mixture can be calculated from knowledge of the vapor pressures of the individual components and their mole fractions.

Numerous methods have been developed for determining the vapor pressure of pure fluids. Several of the more common test methods are the isoteniscope, gas saturation methods, and effusion methods. The use of these methods to determine the vapor pressure of mixtures, such as hydraulic fluids, can introduce errors, and it is difficult to obtain accurate vapor pressure data. Of the above methods, the isoteniscope is probably the most commonly used. Descriptions of the isoteniscope technique and apparatus can be found in Refs. 56 and 57. However, a standardized test procedure has not been adopted, and the apparatus and test procedure vary slightly in different laboratories. When the vapor pressure is presented, it is frequently the vapor pressure of the base liquid. A graph of vapor pressure vs temperature for some of the more common types of hydraulic fluids is shown in Fig. 3-31 (Ref. 58). The vapor pressures of specific hydraulic fluids may differ from those of the examples shown in Fig. 3-31. In an homologous series of liquids, the vapor pressures of the individual liquids vary inversely with their molecular weights. Fig. 3-32 is a graph of vapor pressure vs temperature for several types of liquids and exemplifies the differences in the vapor pressures of two petroleum base hydraulic fluids (MIL-H-5606B and MIL-H-27601A).

An apparatus has been developed for determining the vapor pressure of low-volatility solids and liquids. The apparatus can determine absolute vapor pressures at temperatures up to 1000°F, in a very short period of time, and with relatively simple equipment. The method is based on the kinetic theory of gases, which states that the weight loss of a material per unit time is proportional to the vapor pressure of the material (Ref. 4).

A tentative standard test method (Ref. 59) has been adopted by ASTM for determining the vapor pressure of petroleum products that are nonviscous. The method involves injecting a sample of the liquid into a glass bulb that has been evacuated. The rise in pressure in the bulb, resulting from the sample introduction, is the sum of the vapor pressure of the sample and the partial pressure of dissolved air, practically all of which comes out of solution.

The vapor pressure of hydraulic fluids and other low-volatility liquids is usually expressed in millimeters of mercury. The vapor pressure of more volatile products such as gasoline and solvents is often expressed as the Reid vapor pressure. The Reid vapor pressure is approximately the vapor pressure in pounds per square inch absolute. The method of measuring the Reid vapor pressure of a liquid is described by ASTM D-323-58 (Ref. 60) and Federal Test Method 1201.6 (Ref. 61). It is determined by placing a sample of the fuel (chilled to 32° to 40°F) in a sealed bomb with air at ambient pressure and 100°F and measuring the change of pressure in the bomb. The Reid vapor pressure is a standard measure of volatility in the fuels and solvents industry.

3-2.8.2 Boiling Point

The boiling point becomes important only for relatively pure compounds and is not generally used to describe liquids which are mixtures. It is determined by extrapolation of vapor pressure data or by simply heating a liquid until it refluxes or distills. For liquids that are mixtures, a range of boiling points is obtained rather than a single boiling point. The boiling point temperature range of petroleum products is normally determined by ASTM D-86-66, "Distillation of Petroleum Products". A 100-ml sample of the product is distilled in a prescribed manner, depending upon its nature. Temperature readings taken are the initial boiling temperature of the sample, the maximum boiling temperature, and other temperatures as prescribed percentages of the distilled product are recovered in a condensing unit.

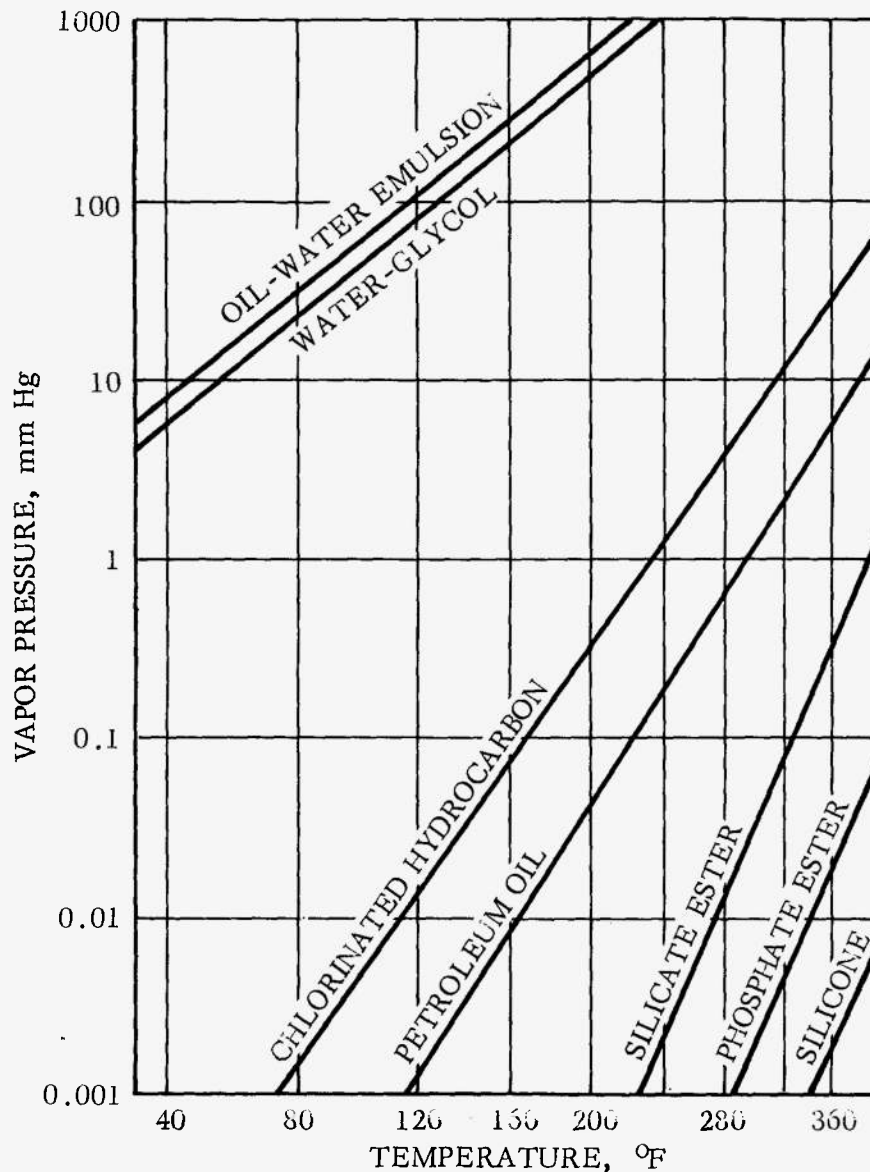


Fig. 3-31. Vapor Pressure vs Temperature of Typical Fluids (Approximate)

[From: F. D. Yeaple, *Hydraulic and Pneumatic Power and Control*⁶⁸. Used by permission of McGraw-Hill, Inc.]

Boiling of a hydraulic fluid in a system can result in failure or component damage. Formation of vapor in control lines, actuators, servomotors, and other components will adversely affect the operation of those components. Boiling on the suction side of the pump will reduce the pump delivery and cause cavitation in the pump.

3-2.8.3 Evaporation

Evaporation loss is widely used in the United States to describe the volatility of liquid products such as

hydraulic fluids, lubricants, and greases. The actual evaporation rate is not an overly important factor in closed-loop hydraulic systems which are not exposed to the atmosphere, but can be important in systems with reservoirs vented to the atmosphere. Several tests for determining evaporation loss have been developed and adopted as ASTM or Federal Test Methods. Most of these tests are essentially the same in that they consist of heating a sample of the liquid in the presence of air and observing the results. They differ in their procedure, apparatus, and method of reporting results.

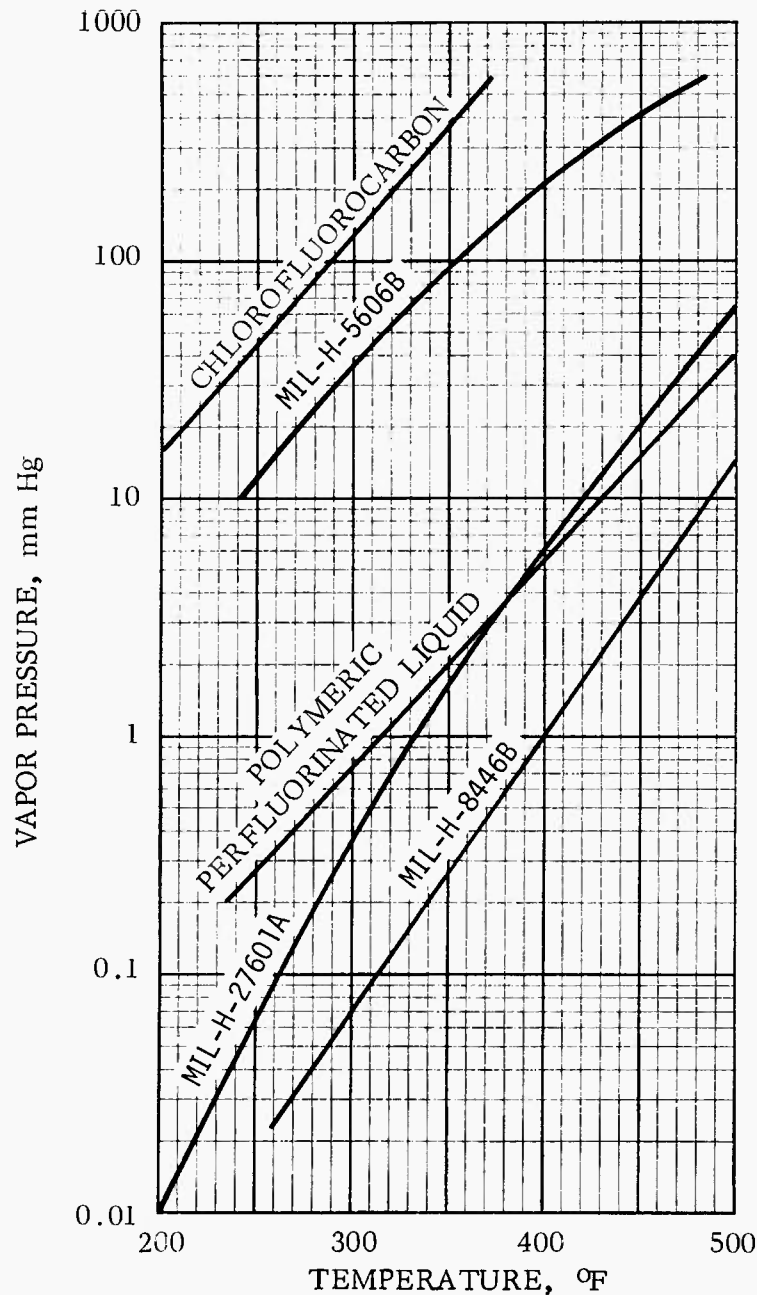


Fig. 3-32. Vapor Pressure vs Temperature of Several Types of Hydraulic Fluids

(1) *Evaporation (Tackiness Test):*

Test Method: Federal Test Method 353 (Ref. 62)

This test method is intended for hydraulic fluids which contain viscosity improvers (such as acryloid polymers). It serves as a means of determining the tackiness of the viscosity improver after the base liquid has been evaporated.

A glass slide is dipped in a sample of the fluid at room temperature and then suspended in an oven. The

oven is heated to the temperature for the period of time called for in the fluid specification. The condition of the fluid on the slide is reported. A fluid is considered to have passed the test if it is still oily and not hard or tacky.

(2) *Evaporation Loss:*

Test Methods: Federal Test Method 351.2 (Ref. 63)

ASTM D-972-56 (Ref. 64)

These methods describe a test procedure for the determination of evaporation loss of lubricating greases and oils at any temperature in the range of 210° to 300°F.

A sample of the fluid is placed in a special container in a bath maintained at the test temperature (see Fig. 3-33). Heated air is passed over the surface of the fluid for 22 hours. The evaporation loss is expressed in percent weight loss of the sample.

Precision:

- (a) Repeatability. 2.5 percent of the mean
- (b) Reproducibility. 10 percent of the mean

(3) *Evaporation Loss—High Temperature:*

Test Method: Federal Test Method 350 (Ref. 65)

This method is the same as the evaporation loss of paragraph (2) above except for the temperatures for the test and the apparatus. Evaporation loss data can be obtained at any temperature in the range of 210° to 1000°F.

3-2.9 DENSITY, SPECIFIC GRAVITY, AND THERMAL EXPANSION

Liquids expand in volume, with a corresponding decrease in density, when heated. The amount of expansion varies with each liquid and is a basic property of

that liquid. The density and the coefficient of cubical expansion are closely related because the coefficient of cubical expansion defines the change in volume (and therefore the change in the density) with a change in temperature.

3-2.9.1 Density

The density is defined as the mass of a unit volume of material at any given temperature and pressure. In the metric system these units are grams per cubic centimeter. It is frequently more convenient to express the density at a given temperature and pressure as the relative density, which is defined by

$$\text{relative density} = \frac{\rho}{\rho_o} \quad (3-21)$$

where

ρ = density at a given temperature and pressure

ρ_o = density at a reference temperature and pressure (standard conditions of 25°C (77°F) and 760 mm Hg are frequently used)

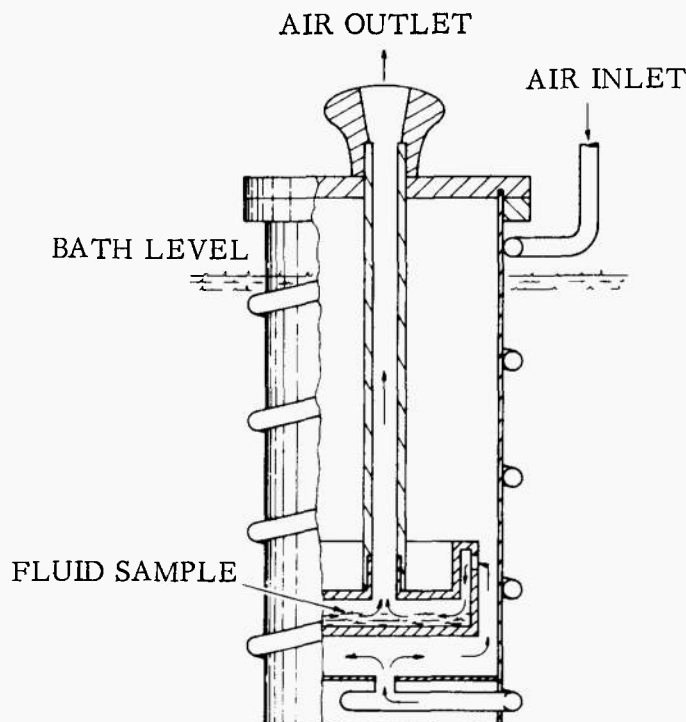


Fig. 3-33. Cut-away Sketch of the Evaporation Loss Apparatus Used in ASTM D-972 Test Method

Density is of great importance when calculating flow of hydraulic fluids through components such as valves, pumps, and motors. The density enters into the flow-energy equations and changes in density will affect the results obtained from the equations. High-density liquids may generally be eliminated from consideration because of weight limitations imposed on the hydraulic system, especially in airborne systems.

Density is a function of both temperature and pressure. An increase in temperature produces a decrease in density. Changes in density due to expansion of fluids between the minimum and maximum system temperature can cause serious malfunctions unless considered in the design of a system. For a high-temperature aircraft or missile hydraulic system operating between the extreme temperatures of -65° and 500°F , the fluid volume can be expected to change up to 35 percent (Ref. 66). Graphs of density vs temperature for several types of fluids are shown in Figs. 3-34 and 3-35.

Density also varies with pressure. An increase in pressure produces an increase in density. However, the normal pressures encountered in most hydraulic systems are not high enough to produce significant changes in density. A graph of relative density vs pressure for a typical MIL-H-5606B hydraulic fluid is shown in Fig. 3-36 (Ref. 67). Pressures as high as 5000 psi (which is higher than the pressures normally encountered in hydraulic systems) produce changes of less than 2.5 percent in the density of the MIL-H-5606B fluid. As the pressures are increased to very high levels, large and significant changes in density are produced. The ASME Pressure-Viscosity Report (Ref. 21) gives density data on several liquids at pressures up to 150,000 psi. Wilson (Ref. 22) reports density-pressure data (see Fig. 3-37) on MLO-60-50 fluid (an ester of trimethylolpropane, the base fluid of MIL-L-9236 oil). Both of these reports indicate that changes in density up to 35 percent are produced at these higher pressures.

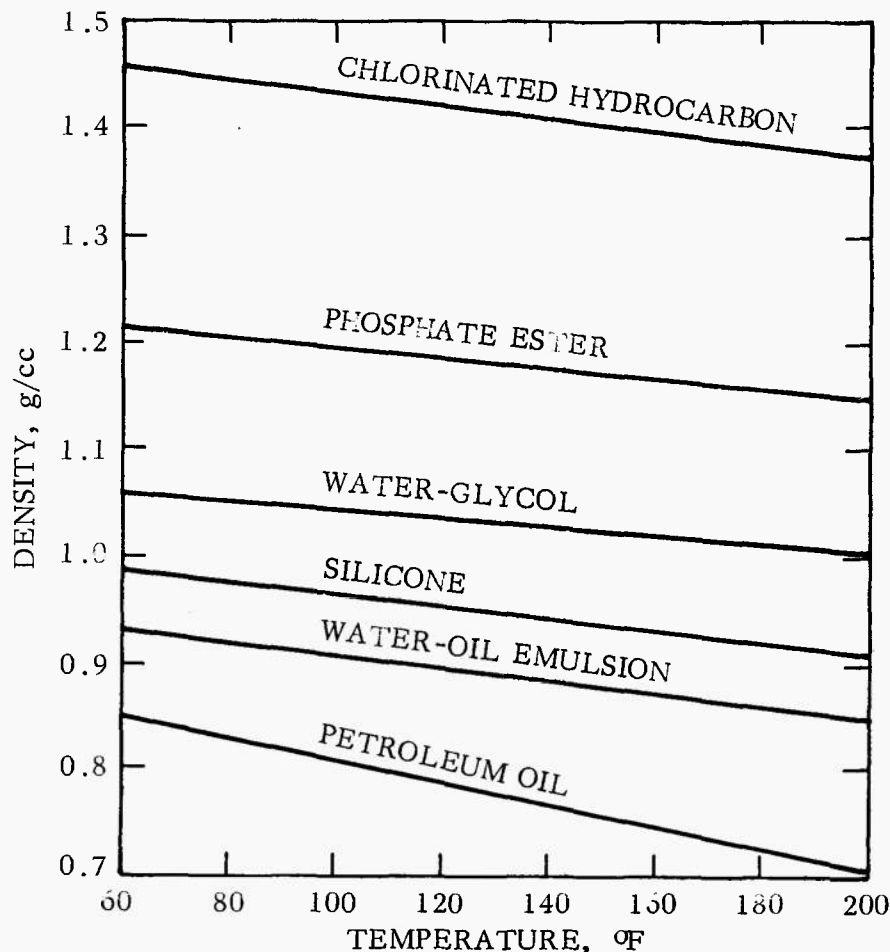


Fig. 3-34. Density vs Temperature of Typical Fluids (Approximate)

[From: F. D. Yeaple, *Hydraulic and Pneumatic Power and Control*⁵⁸. Used by permission of McGraw-Hill, Inc.]

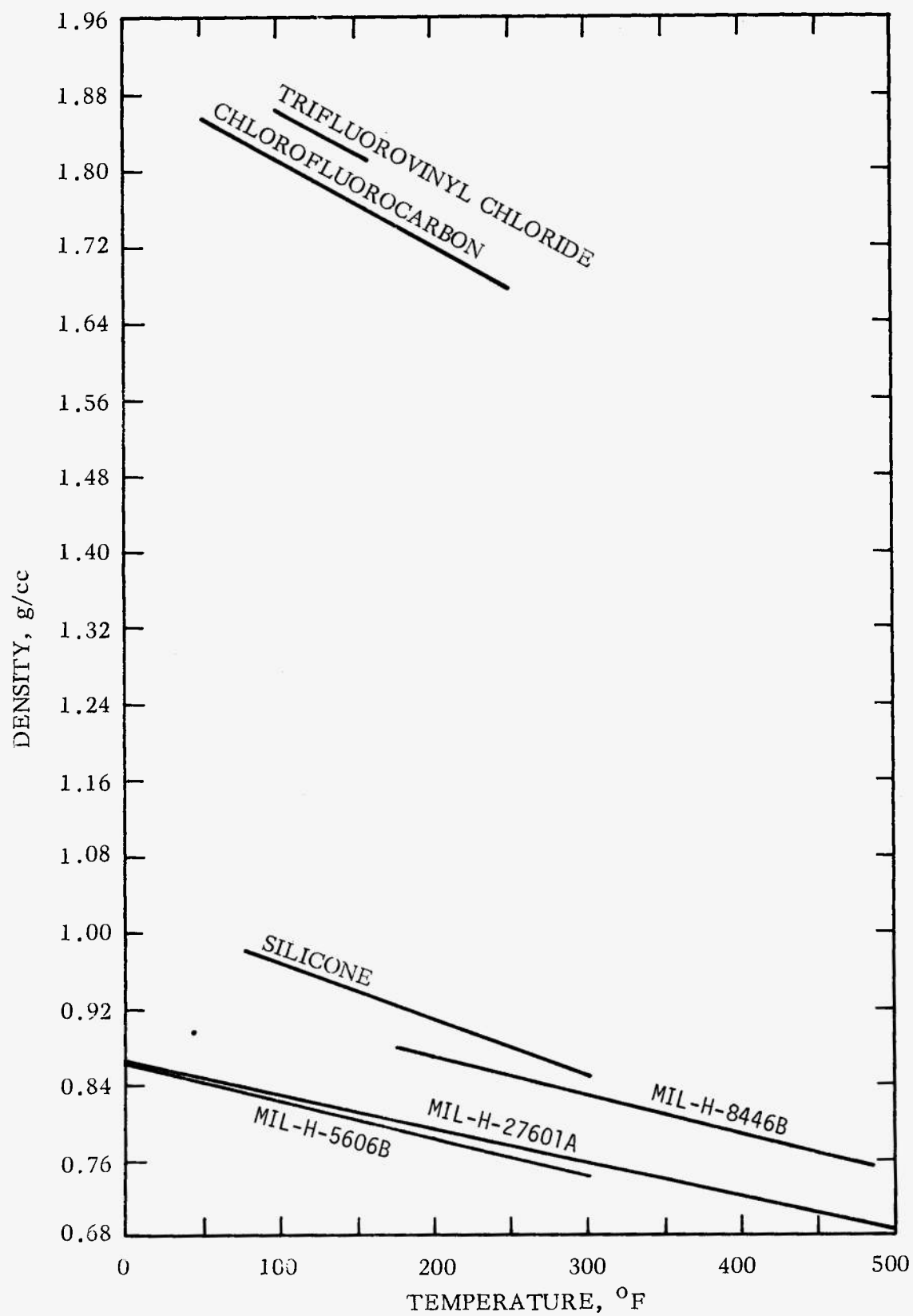


Fig. 3-35. Density vs Temperature of Several Types of Hydraulic Fluids at Atmospheric Pressure

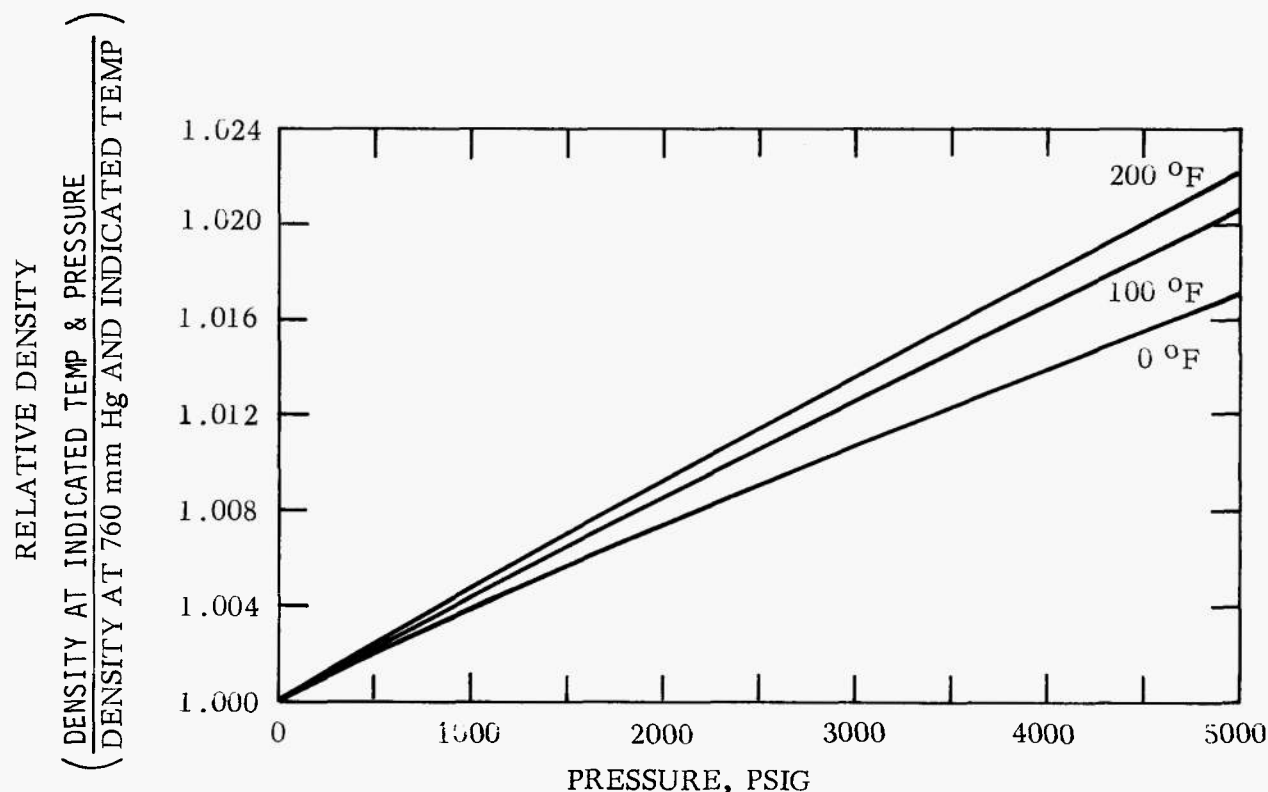


Fig. 3-36. Relative Density vs Pressure at Several Temperatures of a Typical Fluid Conforming to MIL-H-5606B⁶⁷

Researchers at Rock Island Arsenal have conducted extensive studies on the effect of hydraulic fluid density on the performance of artillery recoil mechanisms (Refs. 68, 69). They determined that using a liquid of higher density resulted in shorter recoil lengths and higher pressures. Shorter recoil length may be of value in recoil systems operating in confined areas such as combat vehicles, but consideration must be given to the higher pressures involved.

3-2.9.2 Specific Gravity

The specific gravity of a liquid is defined as the ratio of the mass of a unit volume of the liquid at a given temperature to that of an equal volume of pure water at a standard temperature. The two temperatures are not necessarily the same and both must be indicated in specific gravity data. The common procedure is to have both temperatures equal 60°F (15.6°C) and report the data as "specific gravity at 60/60°F" (the numerator is the temperature of the fluid and the denominator is the reference temperature of the water). Specific gravity, a

dimensionless ratio, is sometimes erroneously used interchangeably with density. They are not the same and should not be confused. They are numerically equal only when water, at 4°C (39.2°F) and 760 mm Hg is the reference liquid. At those conditions, 1 gram of water occupies 1 milliliter or 1.000027 cubic centimeters. The small difference is usually neglected and the terms milliliters and cubic centimeters are considered interchangeable. Specific gravity is as pressure sensitive as density and an increase in pressure will produce an increase in specific gravity.

Specific gravity is very useful in the commercial aspect of the petroleum industry. Almost all liquid petroleum products are packed by volume—barrels, gallons, etc. However, they are frequently shipped or sold on a weight basis and the specific gravity provides a convenient conversion factor. Specific gravity is also useful in determining fuel loads, determining combustion efficiencies, and in other processes that depend on specific gravities of the materials used. The range of specific gravities for petroleum products is about 0.700 to 1.150.

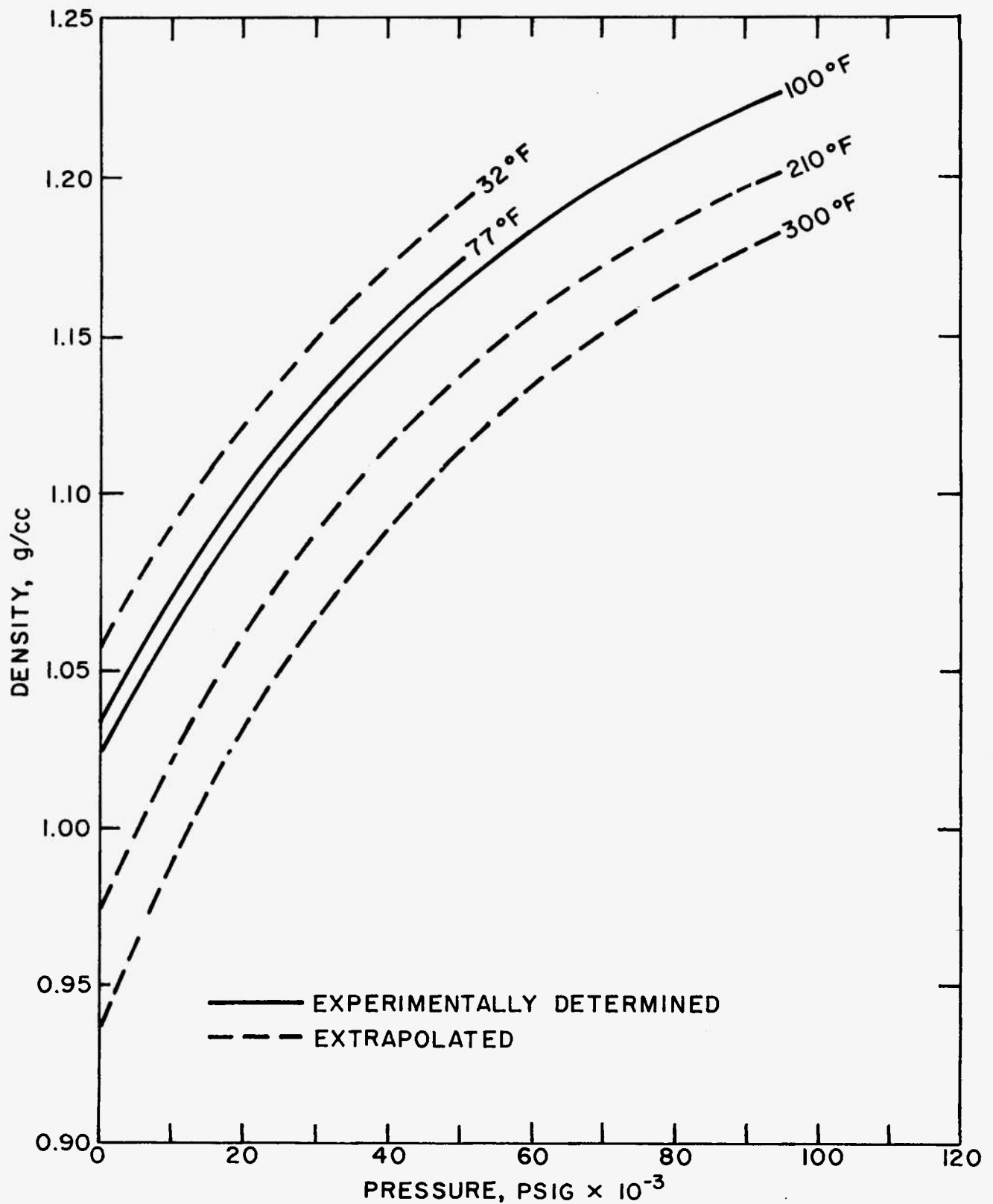


Fig. 3-37. Density vs Pressure at Several Temperatures for MLO-60-50 Fluid (an ester of trimethylolpropane)²²

3-2.9.3 API Gravity

Several methods have been developed to express the weight-volume relationship of a liquid as a whole number. One such method is the American Petroleum Institute (API) Gravity Scale. The scale is based on specific gravity at 60°F (15.6°C) and reports specific gravity as API degrees from 0 to 100. The API scale is an arbitrary scale with zero corresponding to a specific gravity of 1.076 and 100 corresponding to a specific gravity of 0.6762. Therefore, the higher the API Gravity, the lower the specific gravity of a liquid and the less dense the liquid. API gravity is related to specific gravity by the formula

$$\begin{aligned} \text{API Gravity (degrees)} \\ = \frac{141.5}{\text{specific gravity } 60/60^{\circ}\text{F}} - 131.5 \quad (3-22) \end{aligned}$$

For example, water with a specific gravity of 1.000, 60/60°F, has an API Gravity of 10.0.

3-2.9.4 Coefficient of Cubical Expansion

The coefficient of cubical expansion (often called the coefficient of thermal expansion) expresses the change in volume per unit volume with temperature. It has the units of vol/(vol-temperature). Thermal expansion is always accompanied by a change in density or specific gravity and the coefficient of expansion is usually calculated from density (or specific gravity) data determined at various temperatures. It is an average value over the actual temperature range of determination and is not necessarily a linear function. The temperature range where the measurements are made should be stated in all data. Graphs of thermal expansion vs. temperature for three hydraulic fluids are shown in Fig. 3-38.

3-2.9.5 Test Methods for Density and Specific Gravity

(1) API Gravity:

Test Methods: Federal Test Method 401.5 (Ref. 70)
ASTM D-287-64 (Ref. 71)

These methods describe a procedure for determination, by means of a glass hydrometer, *the API Gravity of petroleum products normally handled as liquids and having a Reid vapor pressure of 26 psi or less.

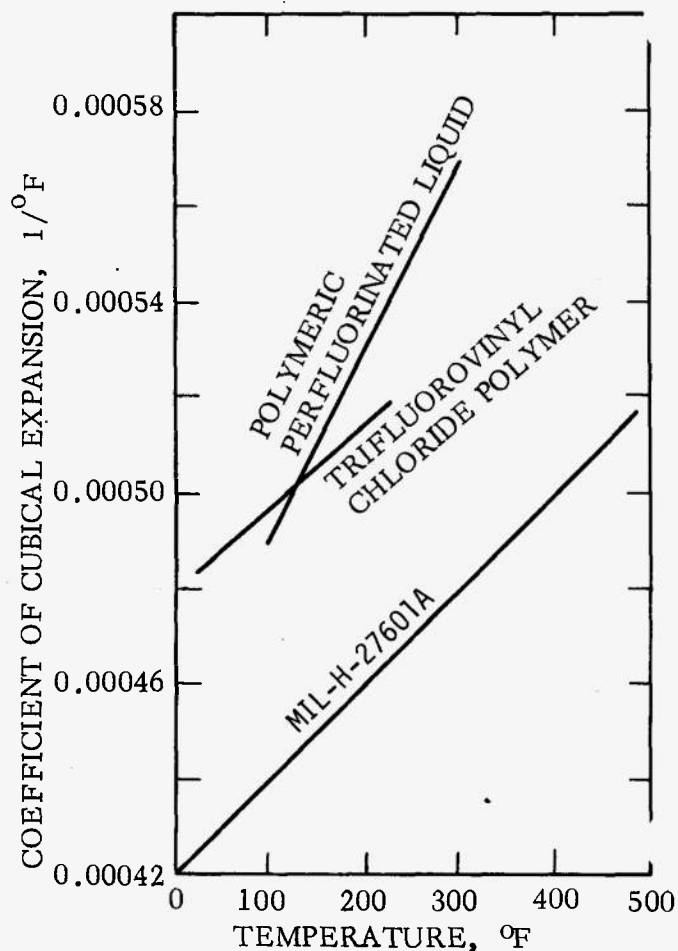


Fig. 3-38. Coefficient of Cubical Expansion vs Temperature of Several Types of Hydraulic Fluids

A sample of the fluid is brought to the proper test temperature and placed in a glass cylinder. An API hydrometer is floated in the fluid and the API Gravity in degrees is read from the hydrometer. The temperature of the sample is noted. All readings are corrected to API Gravity at 60°F by means of standard tables published by ASTM and the Institute of Petroleum (Ref. 72).

Precision: The criteria which should be followed for judging results obtained at temperatures of 60°±18°F are that results should not be considered suspect unless they differ by more than the following amounts:

- (a) Repeatability. 0.2° API
- (b) Reproducibility. 0.5° API

* A hydrometer is a floating instrument for determining the specific gravity of fluids from knowledge of the specific gravity of the hydrometer and the amount of the floating hydrometer that extends above the surface of the fluid.

(2) *Density and Specific Gravity – Lipkin Bicapillary Pycnometer*

Test Methods: Federal Test Method 402.2 (Ref. 73)
ASTM D-941-55 (Ref. 74)

These methods describe the procedure for the measurement of density of hydrocarbon materials that can be normally handled as liquids at the specified test temperatures of 20° and 25°C (68° and 77°F). Application is restricted to liquids having vapor pressures less than 600 mm Hg (approximately 0.8 atmospheres) and viscosities less than 15-20 centistokes at 20°C. Two procedures are provided—Procedure A for pure compounds and mixtures not highly volatile, and Procedure B for highly volatile mixtures. These test methods also provide a calculation procedure for converting density to specific gravity.

A sample of the liquid is drawn into the bicapillary pycnometer (shown in Fig. 3-39) and weighed. It is then placed in a bath at the specified temperature and allowed to come to equilibrium. The height of the fluid in each arm is noted and the volume is determined from the pycnometer calibration. The density and the specific gravity are then calculated from the weight and volume of the fluid sample.

Precision: Results should not be considered suspect unless they differ by more than the following amounts:

- (a) Repeatability. 0.0001 g/ml
- (b) Reproducibility. 0.0002 g/ml

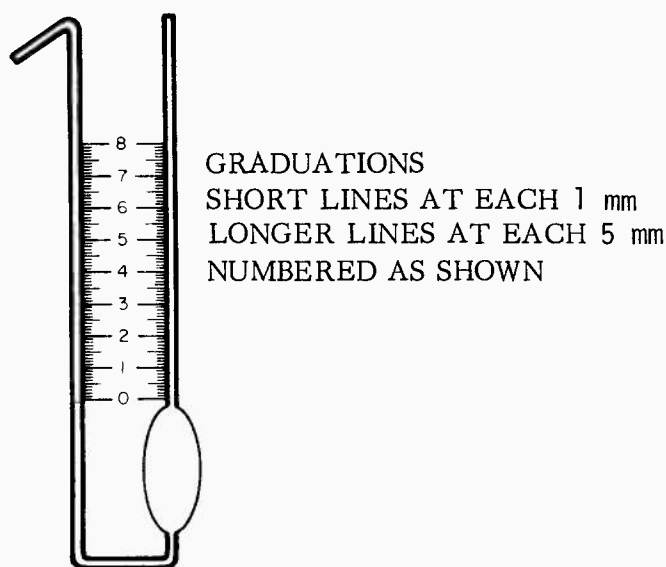


Fig. 3-39. Lipkin Bicapillary Pycnometer for Determining Density and Specific Gravity of Liquids

(3) *Density and Specific Gravity—Bingham Pycnometer*

Test Method: ASTM D-1217-54 (Ref. 75)

This method describes the procedure for determining the density of pure hydrocarbons or petroleum distillates boiling between 90° and 160°C (194° and 230°F) that can be handled normally as liquids at 20° and 25°C (68° and 77°F). Also provided is a calculation procedure for conversion of density to specific gravity.

The fluid sample is introduced into the pycnometer (shown in Fig. 3-40), allowed to come to equilibrium at the test temperature, and weighed. The specific gravity or density is then calculated from this weight and the previously determined weight of water that is required to fill the pycnometer at the same temperature.

Precision: Results with the 25-ml Bingham pycnometer should not differ by more than the following amounts:

- (a) Repeatability. 0.00002 g/ml
- (b) Reproducibility. 0.00003 g/ml



Fig. 3-40. Bingham Pycnometer for Determining Density and Specific Gravity of Liquids

(4) *Specific Gravity—Hydrometer Method*

Test Method: ASTM D-1298-55 (Ref. 76)

This method describes a procedure for the determination, by means of a glass hydrometer, of the specific gravity of crude petroleum and petroleum products normally handled as liquids and having a Reid vapor pressure of 26 psi or less. Results are determined at 60°F or converted to values at 60°F by means of standard

tables published by ASTM and the Institute of Petroleum (Ref. 72).

The sample is poured under prescribed conditions into a clean hydrometer cylinder. The hydrometer is lowered into the sample so that it is floating freely away from the walls of the cylinder. The observed gravity is read directly on the hydrometer scale at the point where the surface of the sample intersects the scale. The temperature of the sample is also measured.

Precision: Results should not be considered suspect when obtained at temperatures differing from 60°F by less than 18°F unless the specific gravity values differ by more than the following amounts:

- (a) Repeatability. 0.0015 g/ml
- (b) Reproducibility. 0.0040 g/ml

3-2.10 HEAT TRANSFER CHARACTERISTICS

The heat transfer properties of a hydraulic fluid can be very important to the design engineer as most hydraulic systems are thermally inefficient. A large portion of the pressure energy supplied to the hydraulic fluid through the pump is dissipated by friction in the valves, motors, actuators, seals, piping, and other components of the system. All of this dissipated energy becomes heat energy and much of it raises the liquid temperature. A knowledge of the heat transfer characteristics of the liquid then becomes essential to determine how high the temperature will rise, and what type and size of heat exchanger will be needed to maintain the liquid at a desirable temperature.

3-2.10.1 Specific Heat

The specific heat of a liquid is a measure of the amount of heat a given quantity of liquid can absorb from the system. It is defined as the heat required to raise a unit weight of liquid one degree of temperature. The specific heat is usually denoted by the symbol c_p or c_v , and its units in the metric system are calorie/(g·°C) and in the English system are Btu/(lb·°F). The subscripts p and v indicate whether the determination of specific heat is made at constant pressure or at constant volume. This distinction becomes important in gases which are highly compressible, but liquids are relatively incompressible by comparison and there is little difference between the two values. In general, however, it is common practice to determine the specific heat of liquids at constant pressure and the symbol c_p is used. Specific heat in the metric system is numerically equal to specific heat in the English system of units.

For a given hydraulic system supplying a given amount of heat to the hydraulic fluid, a liquid with a high specific heat will undergo a smaller temperature rise than will a liquid with a low specific heat. Thus a high value aids in maintaining a lower operating temperature in a system, and in some applications increases the amount of heat that may be removed from a system hot spot without causing degradation of the liquid. Most petroleum-base hydraulic fluids have a specific heat between 0.4 and 0.5 Btu/(lb·°F).

The specific heat increases with temperature for most hydraulic fluids and the temperature should always be stated with the data. A graph of specific heat vs temperature for several hydraulic fluids is shown in Fig. 3-41. Although specific heat varies with pressure, the change is so small over the pressure ranges normally encountered in hydraulic systems that it is neglected.

Numerous methods have been developed to measure the specific heat (Ref. 4). Almost all of these methods utilize some type of calorimeter (essentially an insulated flask). A known volume of the sample is placed into the flask and a known amount of heat is added to the sample. The change in temperature of the sample and the amount of heat added are both recorded. The specific heat is then calculated with corrections being made for heat losses from the calorimeter. An approximation to the specific heat of petroleum liquids is given by the following equation (Ref. 77)

$$c_p = \frac{1}{\sqrt{s}} (0.388 + 0.00045 T) \quad (3-23)$$

where

s = specific gravity at 60/60°F
 T = temperature, °F

3-2.10.2 Thermal Conductivity

Thermal conductivity is one measure of the ability of a material to transfer heat. Heat transfer in operating hydraulic systems is accomplished primarily by convection because of forced liquid mixing. However, thermal conductivity is of importance in the transfer of heat to or from physical boundaries of hydraulic systems. A liquid having a high thermal conductivity will more readily pick up heat in hot system components, such as

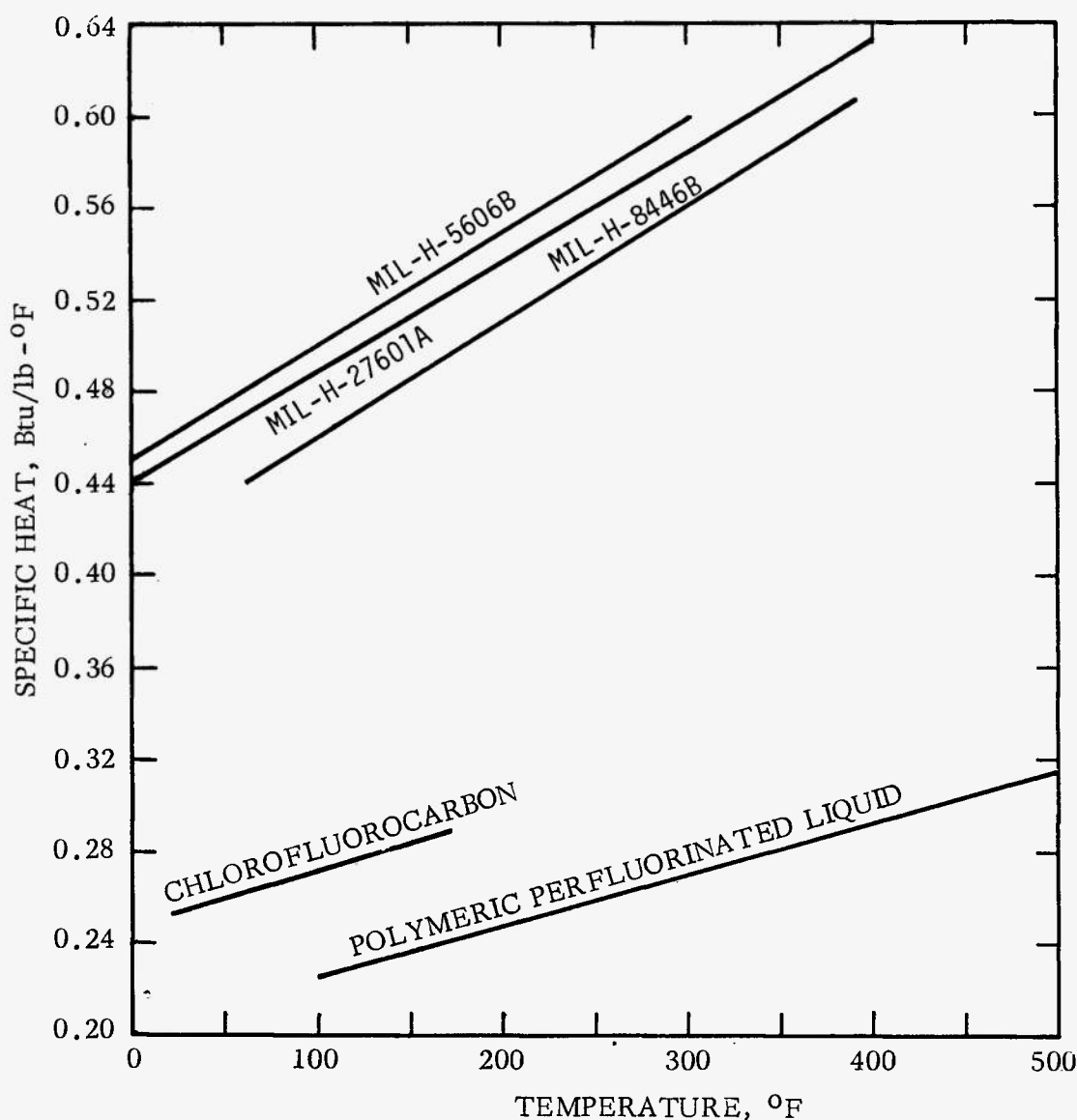


Fig. 3-41. Specific Heat vs Temperature of Several Types of Hydraulic Fluids

valves and pumps, and transfer it to cooler system components such as heat exchangers. Liquids commonly used in hydraulic systems generally have thermal conductivities at room temperature on the order of 0.06 to 0.09 Btu/(hr)(ft²)(°F/ft), and these values normally decrease appreciably with temperature increases. Conversion of units from the English system in Btu/(hr)(ft²)(°F/ft) to the metric system in cal/(sec)(cm²)(°C/cm) can be made by multiplying the values in the English system by 0.00413. A graph of

thermal conductivity of several hydraulic fluids is shown in Fig. 3-42.

Several methods of measuring thermal conductivity have been developed (Ref. 4). Most of these methods consist of placing the sample fluid between two surfaces of known area and heating one surface to a known temperature. The temperature of the other surface and the rate of heat transfer are observed. The thermal conductivity is then calculated.

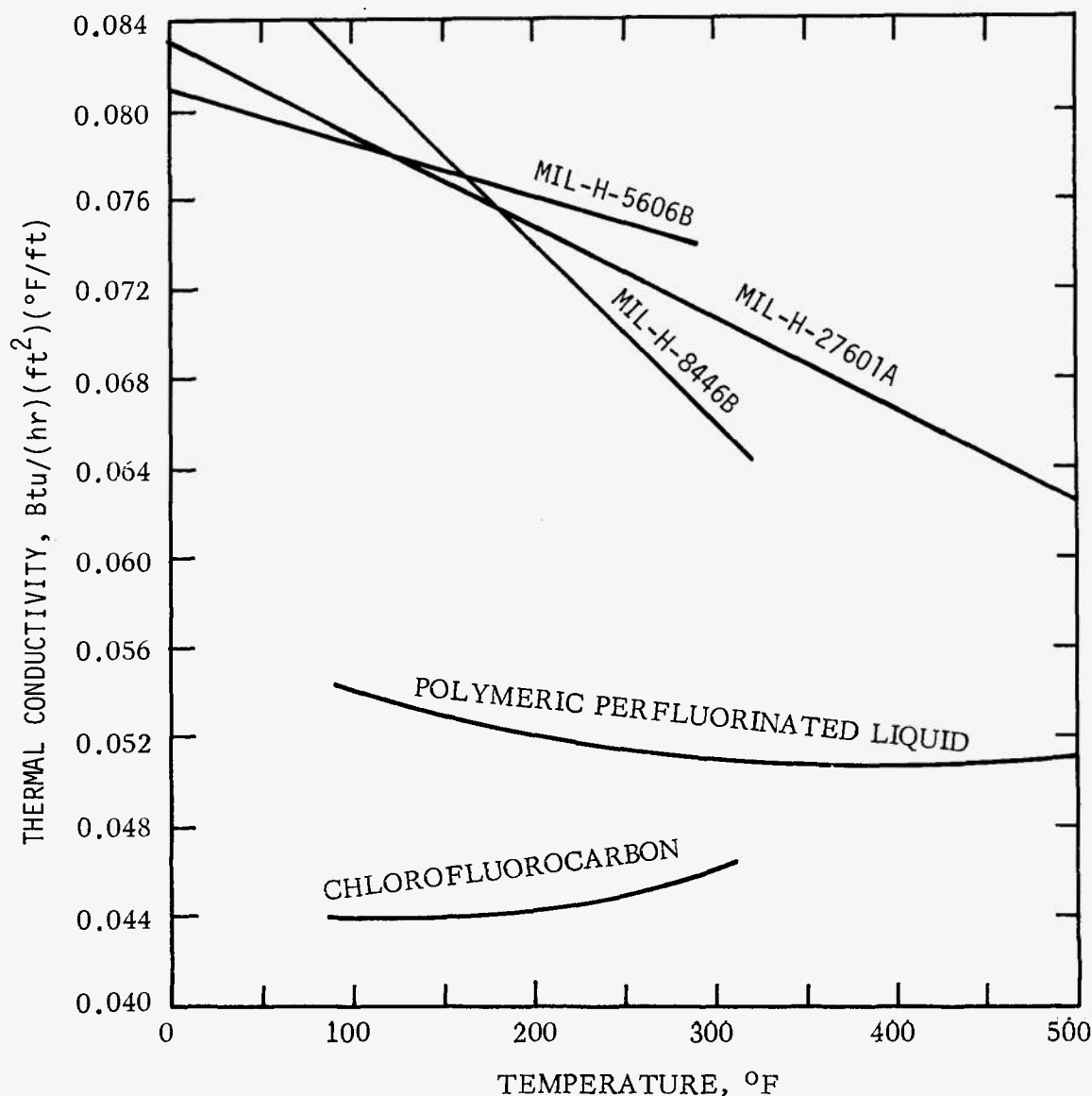


Fig. 3-42. Thermal Conductivity vs Temperature of Several Types of Hydraulic Fluids

3-2.11 COMPRESSIBILITY AND BULK MODULUS

3-2.11.1 Compressibility

Most liquids are thought of as being incompressible. In general, however, all liquids are compressible to some extent. Compressibility of a liquid causes the liquid to act much like a stiff spring. The spring-like action can produce delays in control signals, use energy in compressing the fluid, and affect the gain or amplification of servo systems (Ref. 78). It is usually desirable

to have the hydraulic fluid as stiff as possible, or stated in another manner, to have the compressibility as small as possible.

The coefficient of compressibility is the fractional change in a unit volume of liquid per unit change of pressure. If the compression process is carried out slowly so that sufficient heat is removed to maintain a constant temperature, the resultant value of compressibility is the isothermal compressibility given by (Ref. 4)

$$C_t = \frac{1}{V_o} \left(\frac{\partial V}{\partial P} \right)_t \quad (3-24)$$

where

$$\begin{aligned} C_t &= \text{isothermal compressibility} \\ V_o &= \text{initial volume} \\ (\partial V / \partial p)_t &= \text{rate of change of volume with} \\ &\quad \text{pressure at constant} \\ &\quad \text{temperature} \end{aligned}$$

If the compression takes place so that adiabatic conditions exist (no heat extracted), the result is the isentropic compressibility given by (Ref. 4)

$$C_s = \frac{1}{V_o} \left(\frac{\partial V}{\partial p} \right)_s \quad (3-25)$$

where

$$\begin{aligned} C_s &= \text{isentropic compressibility} \\ V_o &= \text{initial volume} \\ (\partial V / \partial p)_s &= \text{rate of change of volume with} \\ &\quad \text{pressure (at constant entropy)} \end{aligned}$$

In the English system, compressibility has the units of volume/(volume-psi). It is common practice to cancel out the volume terms and express compressibility as (psi)⁻¹. A graph of percent volume compression vs pressure of several liquids is shown in Fig. 3-43 (Ref. 58).

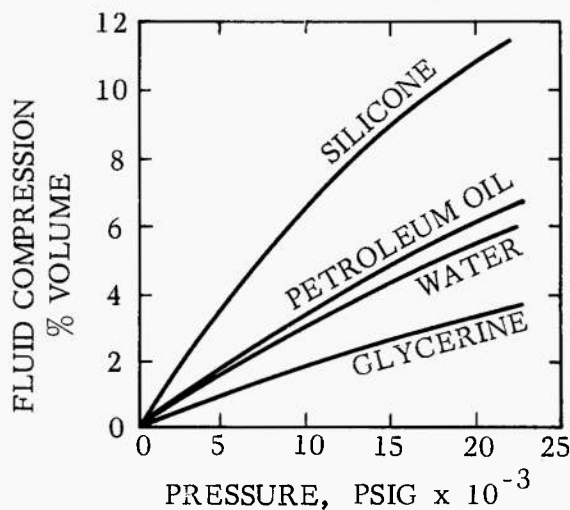


Fig. 3-43. Fluid Percent Volume Compression vs Pressure of Typical Fluids

Differences exist between the isothermal and the isentropic compressibility. For normal situations encountered in hydraulic systems, they are not sufficient to warrant differentiation. However, at high temperatures or pressures, or for certain liquids, the differences can become significant and, when added to the wide

variations due to temperature and pressure, a system can be driven beyond acceptable stability limits (Ref. 66).

3-2.11.2 Bulk Modulus

Bulk modulus, the reciprocal of compressibility, is used in design calculations for hydraulic systems. The units of bulk modulus are psi. The higher the bulk modulus, the less elastic or the stiffer the liquid. High bulk modulus values are usually desirable since the result is a more stable and less elastic system.

Like compressibility, bulk modulus can be either isothermal or adiabatic. The isothermal bulk modulus is sometimes referred to as the static bulk modulus because it is determined at a constant temperature. The isentropic or adiabatic bulk modulus is sometimes referred to as the dynamic bulk modulus. In either case, static or dynamic, bulk modulus may be reported as the secant or the tangent modulus. The names "secant" or "tangent" refer to the relationship the values have to the pressure-volume curve of the liquid (see pars. 3-2.11.2.1 and 3-2.11.2.2). There are then four bulk modulus values possible—isothermal secant, adiabatic (isentropic) secant, isothermal tangent, and adiabatic (isentropic) tangent—and care must be exercised to select the right value for a particular application. Table 3-5 presents the equations for the various bulk moduli. A typical graph of isothermal secant bulk modulus vs pressure is shown in Fig. 3-44.

3-2.11.2.1 Secant Bulk Modulus

The secant bulk modulus (frequently referred to in the literature as mean or average modulus) is defined as the total change in liquid pressure divided by the total change in volume per unit volume of liquid. The secant modulus then is the slope of the secant (drawn between two pressures) of the pressure-volume curve (see Fig. 3-45). It is standard practice to set the initial pressure equal to atmospheric. The secant modulus of a liquid can be thought of as the average pressure required to produce a given volume change per unit volume over a given pressure range.

(1) *Isothermal Secant Bulk Modulus*: The isothermal secant bulk modulus \bar{B}_t is the bulk modulus determined when the liquid is held at constant temperature. It is the modulus value that is applied to systems that change pressure and volume very slowly, allowing heat to flow in or out to maintain a constant temperature. This is the value of bulk modulus most often reported

TABLE 3-5.
BULK MODULUS

Bulk Modulus	Equation	Comment
Isothermal Secant	$\bar{B}_t = -V_o \left(\frac{\Delta p}{\Delta V} \right)_t$	(1) Pressure-volume data obtained at constant temperature
Adiabatic (Isentropic) Secant	$\bar{B}_s = -V_o \left(\frac{\Delta p}{\Delta V} \right)_s$	(2) Pressure-volume data obtained at constant entropy
Isothermal Tangent	$\bar{B}_t = -V_o \left(\frac{\partial p}{\partial V} \right)_t$	(3) No. 1 above
Adiabatic (Isentropic) Tangent	$B_s = -V_o \left(\frac{dp}{dV} \right)_s$	(4) No. 2 above
Sonic	$B_{so} = C^2 \rho$	(5) Sonic modulus is a method of measuring adiabatic tangent
V_o = initial volume Δp = change in pressure ΔV = change in volume dp/dV = derivative of pressure with respect to volume ρ = density of liquid C = speed of sound in the liquid		

for hydraulic fluids. It can be easily determined with relatively simple equipment. Its defining equation is given in Table 3-5.

(2) *Adiabatic (Isentropic) Secant Bulk Modulus:* The adiabatic or isentropic bulk modulus \bar{B}_s is defined by an equation similar to the isothermal modulus. As shown in Fig. 3-45, the isentropic and isothermal secant bulk moduli are defined by the same secant line. The difference is that the data for the isentropic modulus are acquired under adiabatic conditions. The equation defining isentropic secant modulus is given in Table 3-5.

3-2.11.2 Tangent Bulk Modulus

The tangent bulk modulus is defined as the product of the derivative of liquid pressure with respect to volume and the volume under compression. In Fig. 3-45 the tangent bulk modulus is the slope of the tangent drawn at a given point. It is not an average value

over a range of pressures like the secant but represents the bulk modulus at a specific temperature and pressure.

(1) *Isothermal Tangent Bulk Modulus:* The isothermal tangent bulk modulus B_t is the tangent bulk modulus determined when the fluid is held at a constant temperature. Its defining equation is given in Table 3-5.

(2) *Adiabatic (Isentropic) Tangent Bulk Modulus:* The isentropic or adiabatic tangent bulk modulus B_s is defined by an equation similar to the isothermal case except that the total derivative is used. The difference between the isothermal and isentropic tangent bulk moduli is that the data for the isentropic modulus must be acquired under adiabatic conditions rather than under constant temperature conditions.

3-2.11.3 Sonic Bulk Modulus

Most bulk modulus data are determined by the use of mechanical equipment, and the resultant data are the

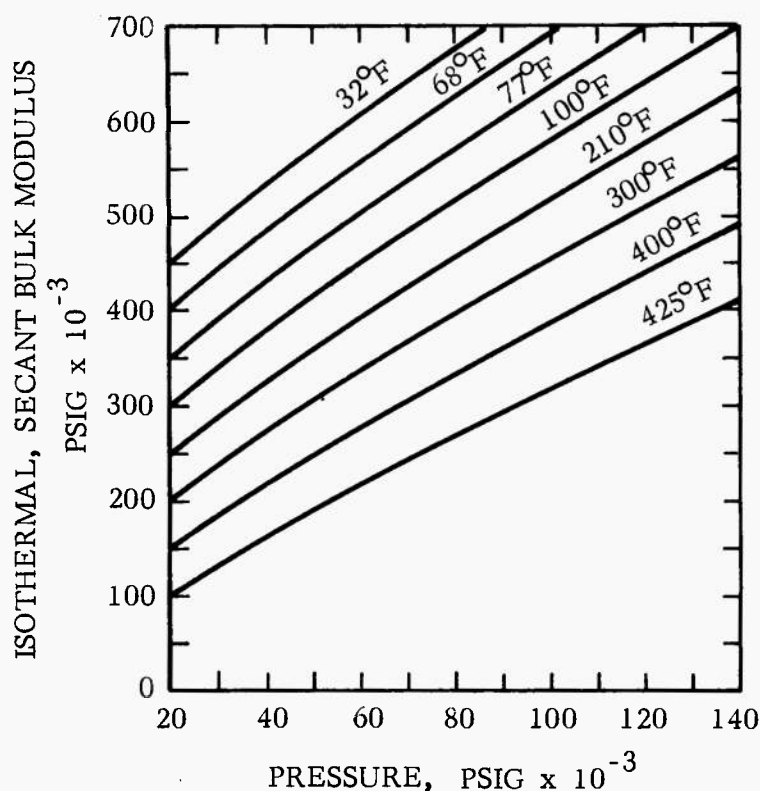


Fig. 3-44. Bulk Modulus vs Pressure—A Generalized Relationship for a Variety of Fluids Over the Range of 32° to 425°F²³

isothermal secant bulk moduli. However, many hydraulic mechanisms operate at relatively high speeds and the heat of compression does not dissipate. Therefore, the process is isentropic, not isothermal. One procedure to obtain the isentropic bulk modulus has been by differentiation of the isothermal data. This involves rather complex analytical procedures and is not a simple procedure. However, it was found that the isentropic tangent bulk modulus could be measured directly with a sonic apparatus. By measuring the speed of sound in the liquid, the isentropic tangent bulk modulus is determined by the equation given in Table 3-5. The speed of sound in the liquid is determined by measuring the time required for a pressure pulse or sound wave to travel through the liquid. This method of determining bulk modulus approaches adiabatic conditions with more accuracy than any other method used, and the very nature of the experimental procedure rules out the existence of an isothermal sonic modulus.

3-2.11.4 Measurement of Bulk Modulus

3-2.11.4.1 Secant and Tangent Bulk Moduli

Secant and tangent bulk moduli are usually determined by obtaining a pressure-volume curve for the liquid. Several experimental methods have been developed.

One method is to compress a known sample of the liquid with a column of mercury. The change in position of the mercury-liquid interface is a measure of the compression of the liquid. Use of capillary tubes of mercury allows easy attainment of high pressures on the order of 1,000 to 2,000 psi.

Another method frequently used is to place a sealed container of the test liquid into a pressure chamber, subject the container to pressure from an external liquid and measure the change in volume of the container. One of the most successful examples of this technique

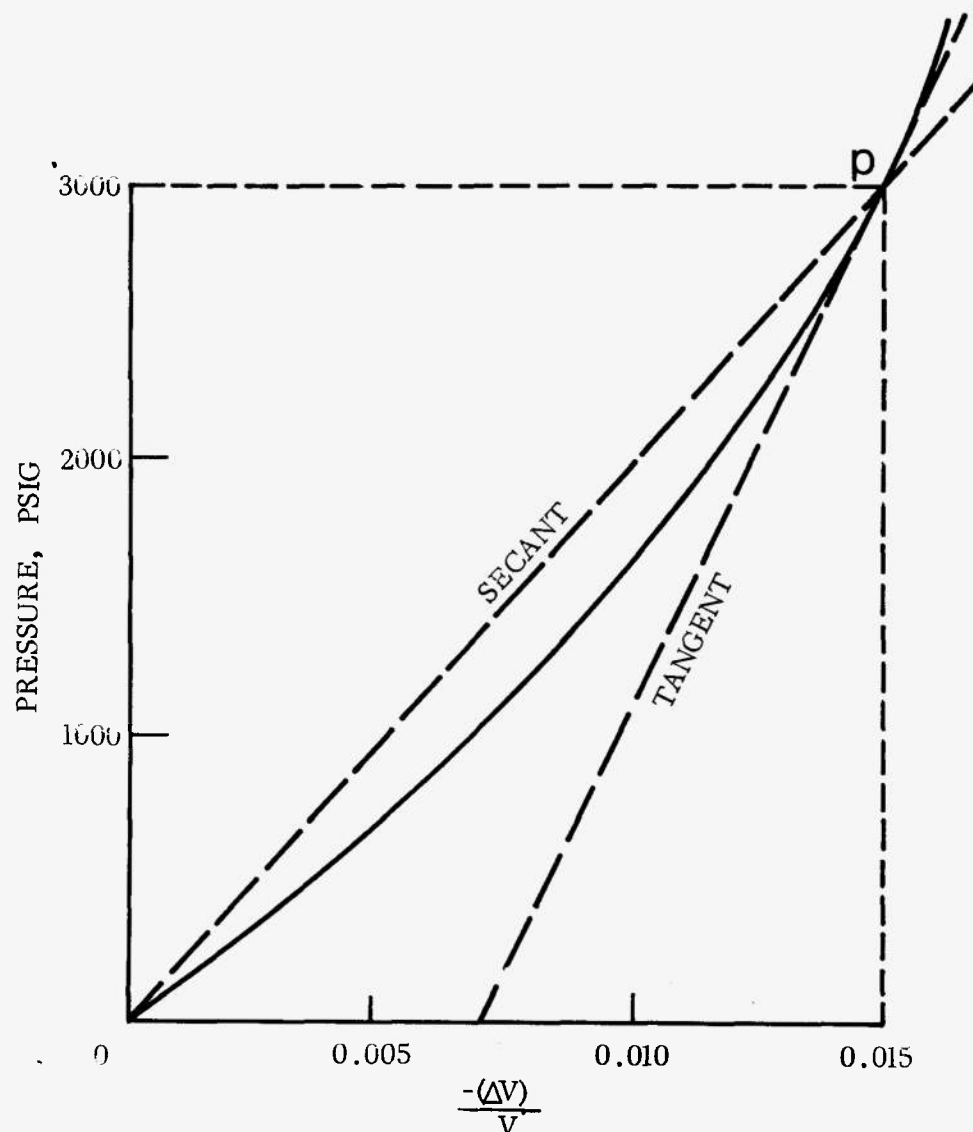


Fig. 3-45. Example Representation of Secant and Tangent Bulk Moduli

is the Bridgeman method. The liquid is placed in a bellows and compression of the bellows causes movement of an electrical contact along a slide wire. This method has the advantage of yielding a continuous plot of pressure vs volume for the experiment. This method was used to determine fluid compressibility in the ASME *Pressure-Viscosity Report* (Ref. 21) and was also used by Wilson (Ref. 22).

A method commonly used in the petroleum industry is to pressurize a known volume of liquid by forcing additional liquid into the container and measuring the volume of liquid expelled when the pressure is released. This method has the disadvantage that it generates only

one datum point per experiment, but it can be done with simple equipment and fairly rapidly.

3-2.11.4.2 Sonic Bulk Modulus

Determinations of sonic bulk moduli are made utilizing ultrasonic speed measurements. Several methods have been developed. These methods determine the speed either by direct measurement of the speed of ultrasonic waves in the fluid or indirectly by determining frequencies which result in interference of the generated wave and the reflected wave from the opposite

side of the container. From the knowledge of path lengths and signal frequencies, the speed can be calculated.

The ultrasonic bulk modulus methods have some advantages over the pressure-volume methods. They allow rapid measurement of bulk modulus and they are frequently more accurate because the measured quantities themselves, rather than their derivatives, are used in calculation of bulk modulus. The sonic methods have a disadvantage in that rather complex equipment is required to measure density and sonic speed in a liquid under pressure. A schematic drawing of a typical apparatus for measurement of bulk moduli by sonic speed is shown in Fig. 3-46 (Ref. 66).

3-2.11.4.3 Estimation of Bulk Modulus (Penn State Method)

Researchers at the Petroleum Refining Laboratory of Pennsylvania State University have developed a procedure for the measurement and prediction of bulk modulus for fluids (Ref. 23). By studying the pressure-volume-temperature properties of a large number of liquids they developed a series of empirical equations for determining liquid bulk modulus at any temperature or pressure once the bulk modulus is known (with high accuracy) at any one condition of temperature and pressure. They have determined that the effect of pressure on the bulk modulus is essentially independent of the liquid molecular structure and the temperature.

Use of their procedure for pressures in the range of 1 to 10,000 psi and temperatures of 0° to 218°C (32° to 425°F) will yield bulk modulus data with an accuracy of ± 5 percent. A brief outline of their method is given.

(1) Bulk Modulus-pressure Equation:

$$\bar{B}_t = \bar{B}_0 + 5.30p \quad (3-26)$$

where

B_t = isothermal secant bulk modulus at gage pressure p and temperature t , °F

\bar{B}_0 = isothermal secant bulk modulus at 0 psig and temperature t , °F

p = pressure, psig

(2) Bulk Modulus-temperature Equation:

$$\left[\log (\bar{B}_{t_1} / \bar{B}_{t_2}) = \beta (t_2 - t_1) \right]_p \quad (3-27)$$

where

\bar{B}_{t_1} = isothermal secant bulk modulus at gage pressure p and temperature t_1 , °F

\bar{B}_{t_2} = isothermal secant bulk modulus at gage pressure p and temperature t_2 , °F

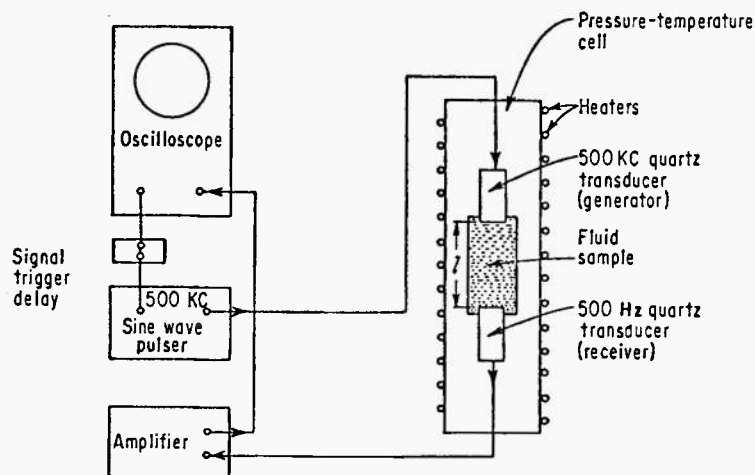


Fig. 3-46. Apparatus for Measurement of Adiabatic Bulk Modulus by Sonic Speed

[From: E. Lewis and H. Stern, *Design of Hydraulic Control Systems*⁶⁶. Used by permission of McGraw-Hill, Inc.]

β = a conversion factor, obtained from Fig. 3-47

(3) *Isothermal Tangent-isothermal Secant Bulk Modulus Relationship*: The isothermal tangent bulk modulus at pressure p is equal to the isothermal secant bulk modulus at $2p$ within 1 percent error.

$$(B_t)_p \approx (B_t)_{2p} \quad (3-28)$$

where

$(B_t)_p$ = isothermal tangent bulk modulus at pressure p
 $(\bar{B}_t)_{2p}$ = isothermal secant bulk modulus at pressure $2p$

(4) *Isothermal Tangent-isentropic (Adiabatic) Tangent Bulk Modulus Relationship*:

$$\frac{B_s}{B_t} = \Gamma = \frac{c_p}{c_v} \quad (3-29)$$

where

B_s = adiabatic tangent bulk modulus
 B_t = isothermal tangent bulk modulus
 Γ = ratio of bulk moduli or specific heats
 c_p = specific heat at constant pressure
 c_v = specific heat at constant volume

(5) *Examples*:

Given:

$$\begin{aligned} \bar{B}_t &= 212,000 \text{ psi} \\ t &= 100^\circ\text{F} \\ p &= 1000 \text{ psig} \end{aligned}$$

(a) Find: \bar{B}_o at 0 psig, 100°F (use Eq. 3-23)

$$\begin{aligned} \bar{B}_t &= \bar{B}_o + 5.30 p \\ [212,000 &= \bar{B}_o + 5.30 (1000)]_{100^\circ\text{F}} \\ [\bar{B}_o &= 206,700 \text{ psi}]_{100^\circ\text{F}} \end{aligned}$$

(b) Find: \bar{B}_t at 10,000 psig, 200°F

1. Eq. 3-24:

$$\begin{aligned} \bar{B}_t &= 206,700 + 5.30 (10,000) \\ [\bar{B}_t &= 259,700 \text{ psi}]_{100^\circ\text{F}} \end{aligned}$$

2. From Fig. 3-47 at 10,000 psig:

$$\beta = 0.001$$

3. Eq. 3-24:

$$\begin{aligned} \bar{B}_{t_1} &= 259,700 \text{ psi} \\ \bar{B}_{t_2} &= ? \end{aligned}$$

$$t_1 = 100^\circ\text{F}$$

$$t_2 = 200^\circ\text{F}$$

$$\log (259,700/\bar{B}_{t_2}) = 0.001 (200-100)$$

$$\bar{B}_{t_2} = 206,100 \text{ psi}$$

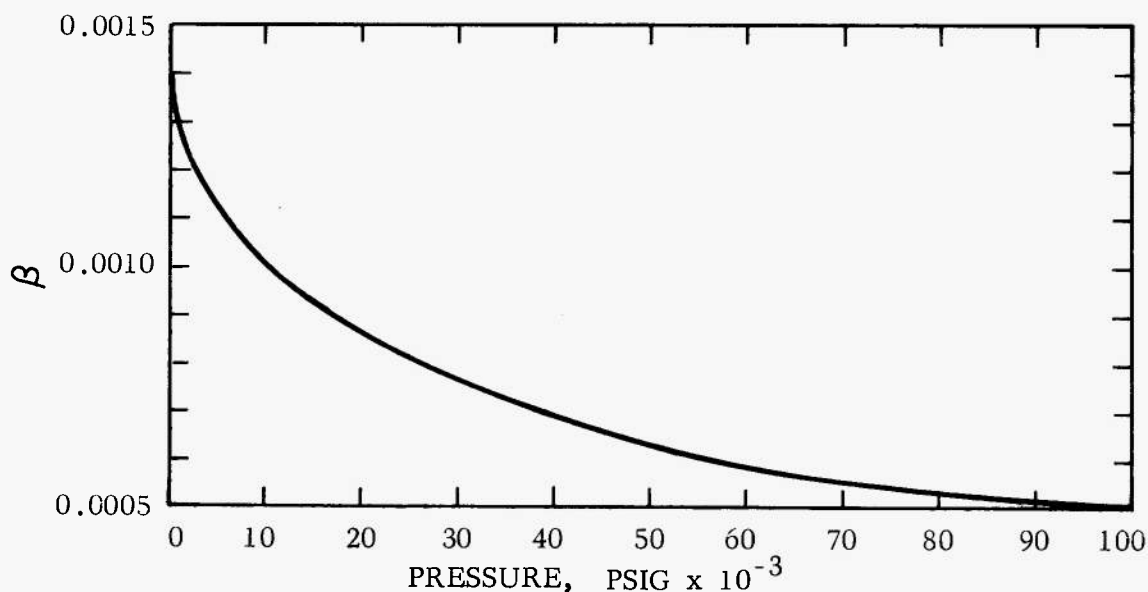


Fig. 3-47. Graph of Constant Used in Eq. 3-27²³

3-2.11.4.4 Estimation of Bulk Modulus (Other Methods)

Other researchers have also developed relationships for predicting the bulk moduli of liquids. Wright (Ref. 79) has developed a method for determining both the secant and tangent bulk modulus of petroleum oils. The method requires knowledge of only the density of the oil at zero psig at a given temperature. By means of a series of graphs, the bulk moduli at any pressure and the given temperatures can be easily determined. Density at an elevated pressure and the given temperature can then be determined by the relationship

$$\rho/\rho_o = 1 - p/\bar{B}_t \quad (3-30)$$

where

$$\begin{aligned} \rho_o &= \text{density at 0 psig, g/cm}^3 \\ \rho &= \text{density at pressure } p, \text{g/cm}^3 \\ p &= \text{pressure, psig} \\ \bar{B}_t &= \text{isothermal secant bulk modulus, psig} \end{aligned}$$

Tichy and Winer (Ref. 80) have developed a method for the prediction of bulk moduli of silicone liquids similar to that of Wright. Their method also uses a series of graphs to convert density at reference conditions to bulk modulus at any temperature and pressure.

3-2.12 EMULSIONS AND FOAMING IN HYDRAULIC FLUIDS

An emulsion is defined as an intimate dispersion of one liquid within another. It is a mixture of two liquids and not a solution with one liquid dissolved in the other. A foam is an emulsion in which the dispersed phase is a gas rather than a liquid. The foaming and emulsion characteristics of a hydraulic fluid are important to system performance because they are mechanisms by which the fluid can pick up and contain contaminants which can affect its properties and functional ability. The contaminants encountered in hydraulic systems are solid particles, gases, and liquids. Contamination with gases can produce foams, and contamination with liquids can produce emulsions. The discussion herein will be limited basically to contamination with air (gas) and water (liquid).

3-2.12.1 Emulsion Characteristics

An emulsion is unstable and will eventually result in a separation of its components. However, the time required for this separation may vary from several seconds to weeks or months. The separation time of an emulsion formed in a hydraulic fluid is determined by the properties of the fluid and any additives it may contain (see Chapter 5), and by the contaminant. An emulsion of water and a hydraulic fluid is undesirable. Ease of separation of the water from the hydraulic fluid then becomes essential.

Water forms two types of emulsions with hydraulic fluids—oil-in-water where the water is the continuous phase and water-in-oil where the oil is the continuous phase. The common type of emulsion forming in hydraulic fluids contaminated with water is an oil-in-water emulsion. Since water is the continuous phase, there is a drastic decrease in lubricating ability, increased rusting, and a possibility of increased viscosity.

Some fire-resistant hydraulic fluids are formulated as water-in-oil emulsions. Emulsion stability of these fluids is, of course, required.

Water can enter a hydraulic system in various ways. Leaks in heat exchangers, condensation of moisture in containers or system reservoirs, and accidental contamination are the usual methods. Once the water is in the system, it is subjected to agitation in the pump and other parts of the system where turbulent flow exists. This mixing produces an emulsion of the hydraulic fluid and water. Water which is thus mixed with the hydraulic fluid can cause rusting, a loss of system efficiency, defective lubrication, increased leakage, and increased oxidation of the hydraulic fluid (Ref. 20). The emulsion will also affect system performance by forming sticky slimes which foul pumps; corrode cylinders and other elements of the hydraulic system; and, in general, produce unsatisfactory performance.

In order to reduce the adverse effects of an oil-and-water emulsion, it is usually desirable to use a hydraulic fluid which has good water-separation characteristics. The hydraulic fluid and the water will then separate quickly in the system reservoir, with the water floating to the top or to the bottom, depending on the density of the hydraulic fluid.

Many materials can function as emulsifying agents and increase the tendency of a hydraulic fluid to form an emulsion. Small concentrations of these materials are usually most effective. Materials which act as emulsifiers can be introduced into a hydraulic system in a number of ways—as impurities in the base stock, as products formed from oxidation during use, and as additives which perform other functions but have

emulsifying properties. Thus, a hydraulic fluid which normally has good water separation characteristics can be changed while in use in the system to a hydraulic fluid which will readily form emulsions.

It should be pointed out that hydraulic fluids which are emulsions of water-in-oil have been proposed and used satisfactorily as fire-resistant hydraulic fluids. In such types of hydraulic fluids it is essential that the oil have good emulsifying properties so that the water will not readily separate from the oil. Water-in-oil emulsion hydraulic fluids are being extensively used by the Bureau of Mines in machines and devices that are operated in coal mines (Ref. 81).

3-2.12.2 Foaming Characteristics

A foam is a dispersion of a gas in a liquid. In general, foaming is undesirable in hydraulic systems. The presence of air in the hydraulic fluid can cause a loss of system efficiency, defective lubrication, and loss of fluid by overflow of the foam. Air can be introduced into a hydraulic system in several ways. It can come from open reservoirs, leakage on the suction side of the pump, seal leakage, or be introduced when filling the system.

Much of the air in a hydraulic system will often be dissolved in the high pressure liquid at the discharge side of the pump. The air that remains dissolved in the liquid does not create a foam. However, as the liquid enters low-pressure areas of the system, the excess air can come out of solution and form bubbles which can be carried with the liquid through the system. Foam can also be formed in any part of the system where the liquid experiences excessive agitation, such as in gears, bearings, valves, and other components. If the liquid has good foam-suppressing capability, the excess bubbles will be carried to the reservoir and released.

Undissolved air causes irregular action of cylinders and valves because the liquid no longer has a high degree of incompressibility. Air bubbles, when compressed to a high pressure, will produce a localized high temperature. It can be shown that if air is adiabatically compressed from atmospheric pressure to 100 psi, the theoretical temperature of the air would be 485°F. At a compression of 3,000 psi, the theoretical temperature would be 2,020°F. These high temperatures may not be noticeably reflected in raising the reservoir temperature, but will cause oxidation of the surrounding liquid film and the formation of contaminants (Ref. 20).

Foaming characteristics are usually discussed in terms of foaming tendency and foam stability. Foaming

tendency is a measure of the ability of a liquid to form a foam under specified conditions that would promote foaming. It is usually desirable to have as little tendency to foam as possible. Foam stability is a measure of the tendency of a liquid to maintain a foam once it has been established. The lower the foam stability, the faster the foam will collapse and release the entrapped air.

Much like emulsion characteristics, foaming characteristics can be influenced by a number of variables. Small amounts of contaminants and oil oxidation products of the liquid generally increase the foaming characteristics. Researchers at Rock Island Arsenal have found that viscosity, temperature, grease contamination, and water contamination all affect the foaming characteristics of hydraulic fluids and liquids used in recoil mechanisms (Ref. 82). Their data indicate a general trend, with exceptions, that increased viscosity will be accompanied by greater foaming tendency and foam stability. The liquids tested showed a decrease in foaming tendency and in foaming stability with an increase in temperature. Contamination with grease in small amounts (1 to 5 percent) produced significant increases in foaming tendency and foam stability. Contamination with water produced erratic results. Very small concentrations of water, 0.08 percent, did not have much effect. With higher concentrations of water (1 to 5 percent), foaming tendency increased. Foam stability increased, at lower temperatures, with increased water concentration; but at the higher temperatures, the foam stability was decreased with the larger percentage of water.

3-2.12.3 Tests for Emulsion and Foaming Characteristics

(1) *Emulsion Characteristics:*

(a) *Emulsion Characteristics of Steam-Turbine Oils:*

Test Method: ASTM D-1401-64 (Ref. 83)

This method is intended for testing steam turbine oils but may be used to test liquids of other types. The method describes a procedure for measuring the ability of oil and water to separate from each other.

A 40 ml sample of the test liquid and 40 ml of distilled water are stirred for 5 min in a graduated cylinder with a flat paddle turning at 1,500 rpm. The time, in multiples of 5 min, required for the emulsion to be reduced to 3 ml or less is reported. If the emulsion is more than 3 ml after 1 hr, the test is discontinued and

the amounts in ml of oil, water, and emulsion remaining are recorded. The results are reported as a series of four numbers—the number of ml of oil, the number of ml of water, the number of ml of emulsion, and the test time. Example:

Results	Comment
40-40-0(20)	Complete separation in 20 min
40-37-3(20)	Emulsion reduced to 3 ml in 30 min test was terminated
39-35-6(60)	More than 3 ml of emulsion remained after 60 min—39 ml of oil, 35 ml of water, 6 ml of emulsion

(b) *Emulsifying Tendency:*

Test Method: Federal Test Method 3201.5 (Ref. 84)

This method is used for determining the emulsifying tendency of petroleum and petroleum-like products.

A 40 ml sample of the oil or liquid to be tested is mixed in a graduated cylinder with a 40 ml sample of an emulsifying agent (distilled water, sodium chloride solution, or synthetic sea water as required by the fluid specification). The cylinder is immersed in a bath (see Fig. 3-48). The mixture is stirred at 1,500 rpm for 5 min at the temperature specified by the liquid specification. The resulting emulsion is allowed to remain undisturbed at the test temperature and for the time required by the liquid specification. It is then examined for any separation and reported whether the end product confirms to the liquid specification.

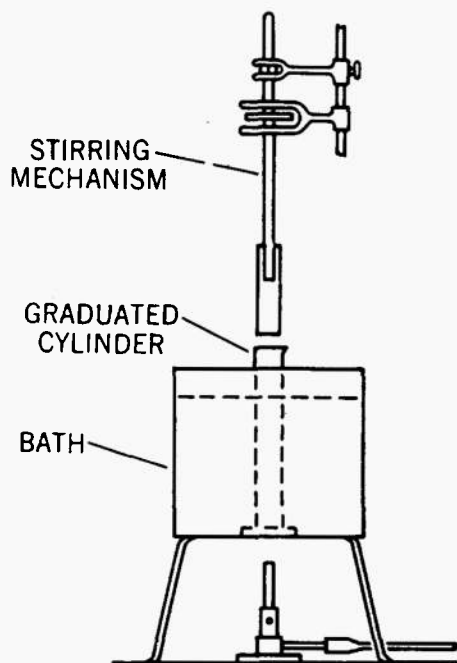


Fig. 3-48. Emulsion Test Apparatus

(2) *Foaming Characteristics:*

Test Methods: Federal Test Method 3211.3

(Ref. 85)

ASTM D-892-63 (Ref. 86)

These methods are intended for the determination of the foaming characteristics of lubricating oils at specified temperatures. A means of empirically reading the foaming tendency and the stability of the foam are described.

A 190 ml sample of the liquid to be tested is placed in a 1,000 ml graduated cylinder (see Fig. 3-49). The sample is maintained at a temperature of 75°F and blown with air for 5 min. The volume of foam is measured. The sample is allowed to settle for 10 min and the volume of foam again measured. The test is next carried out at 200°F on a second sample and then repeated on the second sample at 75°F. Foaming tendency is reported as the total volume of foam in milliliters formed during the 5-min air blowing period. Foam stability is reported as the milliliters of foam remaining after the 10 min standing period. The foaming requirements of 3 Military Specification liquids are shown in Table 3-6.

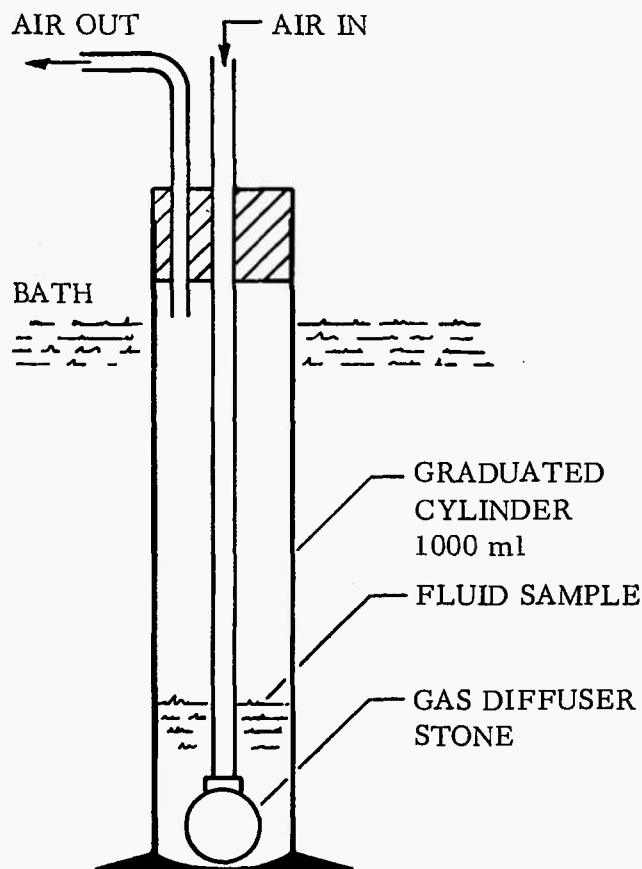


Fig. 3-49. Foaming Test Apparatus

TABLE 3-6.
FOAMING REQUIREMENT OF MILITARY SPECIFICATIONS

Fluid	Temperature, °F	Foaming Tendency	Foam Stability
		Foam vol, ml, at end of 5-min blowing period	Foam vol, ml, at end of 10-min settling period
MIL-H-5606B	75	65 (max)	Complete Collapse
MIL-H-8446B	75	600 (foam + fluid)	Complete Collapse
MIL-H-27601A	75	15 (max)	Complete Collapse
	200	75 (max)	Complete Collapse
	75	75 (max)	Complete Collapse

Precision: Results should not be considered suspect unless they differ by more than the following amounts at the end of the 5 min blowing period:

- (a) Repeatability. 10 ml or 15 percent of average (whichever is greater)
- (b) Reproducibility. 10 ml or 38 percent of average (whichever is greater)

3-2.13 GAS SOLUBILITY

Hydraulic fluids, like other liquids, tend to dissolve any gases that may be in contact with them. The amount of gas dissolved by a particular liquid depends upon the composition of the gas, the composition of the liquid, the temperature, and the pressure. At room temperature and atmospheric pressure, between 5 and 15 percent air, by volume, can be found in solution in hydraulic fluids. A distinction should be made between dissolved gases and trapped or entrained gases. The dissolved gases have virtually no effect on the physical properties of the liquid. They become important only when they are evolved from solution in the form of bubbles creating a foam or a pocket of gas in the system. Once the gas has evolved from solution, the physical properties of the liquid-gas mixture are strongly influenced by the resulting foam (Ref. 66).

The solubility of gases in liquids is generally considered to be inversely proportional to the temperature (Ref. 4) and directly proportional to the pressure. Log-log graphs of gas solubility vs temperature are linear over moderate ranges of temperature (Ref. 66). Leslie

(Ref. 78) has reported that the solubility of gases in many lubricating oils increases with rising temperature. Increases in the solubility of nitrogen in two petroleum oils at 350°F over that at room temperature are shown in Fig. 3-50. This figure also shows that increasing pressure has a much greater effect on nitrogen solubility in distillate white oil than does increasing temperature. In general, pressure has a greater effect on gas solubility than does temperature, but not for all liquids. In Fig. 3-50, temperature is the more significant factor in the case of the naphthenic oils. Increases in the solubility of air with increasing pressure for some different type hydraulic fluids is given in Fig. 3-51. It should be noticed that air solubility in silicone and petroleum oils increases more rapidly with increasing pressure than it does for the polar water base or phosphate ester type oils.

Since solubility limits are affected both by temperature and pressure in a given liquid, changes in temperature and pressure occurring within the system can result in dissolved gases being expelled from solution. Once this happens, the evolved gas bubbles can constitute up to 15 percent of the total liquid plus foam volume and have serious effects on the hydraulic system performance (Ref. 66). Pump delivery will be reduced and the pump is subject to cavitation damage. The compressibility of the hydraulic fluid-foam mixture will be increased, its bulk modulus decreased, and control stability and component life will suffer. Even when system design has provided for such eventuality, it will still take time for the entrapped gas to be transported back to the reservoir where it can be separated from the hydraulic fluid. Reports of hydraulic system

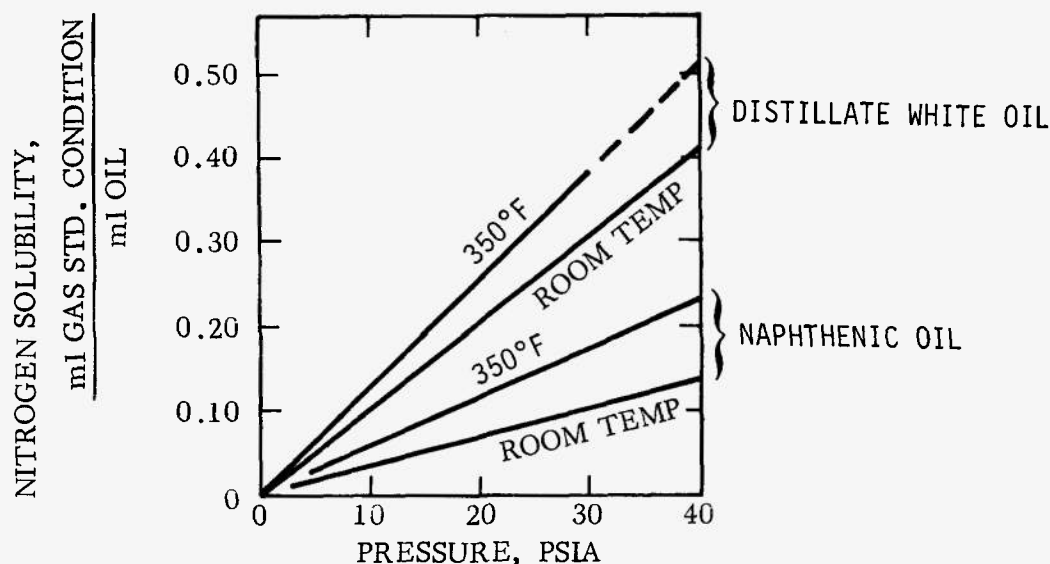


Fig. 3-50. Nitrogen Solubility vs Pressure of Two Petroleum Products

[From: R. L. Leslie, *The Relation of Fluid Properties and High Temperature Hydraulic Performance*⁷⁸. Used by permission of ASLE]

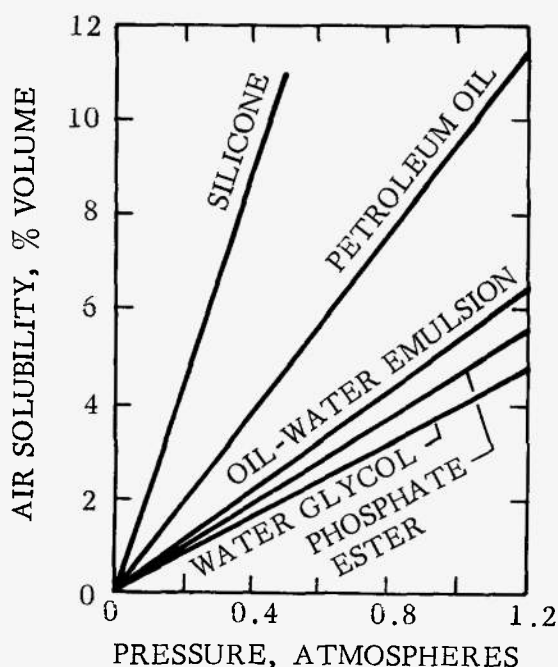


Fig. 3-51. Air Solubility vs Pressure of Typical Fluids

[From: F. D. Yeaple, *Hydraulic and Pneumatic Power and Control*⁵⁸. Used by permission of McGraw-Hill, Inc.]

malfunctions have frequently been traced to air separation problems. Dead-ended or single line systems similar to simple hydraulic brake systems are particularly prone to air evolution and entrapment (Ref. 66). A small amount of liquid circulation built into such systems can help to relieve the problem.

3-2.14 LOW-TEMPERATURE STABILITY

3-2.14.1 General

Hydraulic fluids are often stored for prolonged periods of time at low temperature. During this storage, the liquid should not undergo any permanent changes in its properties or show evidence of gelling, crystallization, or separation of any of its components. Gelling is the formation of jelly-like materials due to coagulation of a component or components of the liquid. Crystallization is the formation of crystals or crystalline material by a component or components of the liquid. Separation is the removal from suspension or solution of components or additives in the liquid. Many specification liquids, however, will be deemed to have satisfactory low-temperature stability if any separated components will readily return into solution at the lowest anticipated operating temperature.

Low-temperature properties of hydraulic fluids become important in storing fluids in cold environments or when hydraulic systems are subject to periods

of nonoperation in cold environments. Formation of gels, crystals, or separation of components could cause clogging of filters, plugging of small orifices and clearances, or lack of lubrication to vital components.

3-2.14.2 Test Methods for Low-temperature Stability

(1) *Viscosity Stability at Low Temperature:*

Test Method: Federal Test Method 307 (Ref. 87)

Change in viscosity of fluids subjected to low temperatures is often used as a criterion of low-temperature stability. This method describes a procedure for determining the viscosity stability of transparent fluids at -65°F . In this method, a sample of the lubricant is placed in a glass capillary-type viscometer in a bath at -65°F . The kinematic viscosity of the sample is then determined. The viscometer and the sample are kept in the bath at -65°F for 72 hr and determinations of the kinematic viscosity are made at intervals throughout the 72-hr period. Changes in viscosity with time provide a measure of low temperature storage instability.

(2) *Gelling, Crystallization and Separation:*

Test Method: Federal Test Method 3458 (Ref. 88)

This method is used for determining the tendency of components of finished oil blends to be incompatible or to form gels during low temperature exposure.

A 100-ml sample of the liquid to be tested is placed in a glass jar and stored for 72 hr at the temperature required by the liquid specification. At the end of the 72-hr period the sample is removed from storage and immediately examined visually for evidence of gelling, separation, or crystallization. If there is any evidence of gelling, separation, or crystallization, the liquid is reported as unstable at the specified temperature.

(3) *Turbidity:*

Test Method: Federal Test Method 3459 (Ref. 89)

This method is used for determining the stability at low temperature of finished liquid blends.

An 8-oz sample of the liquid to be tested and a 250-ml sample of a standard composed of barium chloride, sulfuric acid, sodium hydroxide, and distilled water are stored at the temperature and for the number of hours required by the liquid specification. At the end of the storage period, the standard is shaken vigorously for 10 sec. The liquid sample is also shaken vigorously for 10 sec. The turbidity of the sample liquid is compared to that of the standard and reported as less than, more than, or equal to the standard. Also reported is any evidence of gelling, crystallization, or solidification of the sample liquid.

3-2.15 SEDIMENTATION

Sediment is anything that settles out of a liquid. In hydraulic fluids and lubricating liquids, the definition of sediment is usually restricted to insoluble products that are present in the liquid because of refining or production processes, or because of chemical reactions that occur in the hydraulic system during use. Sedimentation is usually distinguished from contamination which is any undesirable matter, soluble or insoluble, that is introduced into the hydraulic fluid because of improper handling or storage, use of unclean hydraulic systems, leaks in systems, etc. Contamination is discussed in Chapter 6. Sedimentation is present—as dust, dirt, metal, and rust particles picked up from piping and storage vessels—in most new commercial hydraulic fluids as a result of production and refining. Sedimentation in used hydraulic fluids would include these solids as well as metal wear particles, corrosion products, oil oxidation products, or other insoluble oil degradation products.

Sedimentation can become quite critical in hydraulic systems that have close-tolerance moving parts or small orifices. The sediment can settle in these areas and produce a tarnish or sludge which can seriously hamper the operation of the system. Furthermore, sediment can clog filters and reduce their efficiency. Candidate hydraulic fluids have been known to be rejected, even though they satisfied all specification requirements, because they experienced sufficient chemical changes to produce excessive amounts of sediment.

The procedure for testing for trace sediments in lubricating liquids is given by Federal Test Method 3004.4 (Ref. 90) and ASTM D-2273-64T (Ref. 91). These methods describe the procedure for the determination of trace amounts less than 0.05 volume percent of sediment in lubricating liquids. A 50-ml sample of the test liquid is mixed with 50 ml of naphtha in a trace sediment tube (Fig. 3-52) and centrifuged at a given speed for 10 min. The mixture is decanted and the sediment is left in the tube. Another mixture of 50 ml naphtha and 50 ml test liquid is mixed in the same tube and again centrifuged for 10 min. The final volume of the sediment is noted and the results are reported as the volume of sediment/100 ml of sample liquid.

Precision: Results should not be considered suspect unless they differ by more than the following amounts:

Sediment, %	Repeatability	Reproducibility
0.000-0.002	0.001	0.001
0.003-0.005	0.001	0.002
0.006-0.01	0.002	0.003

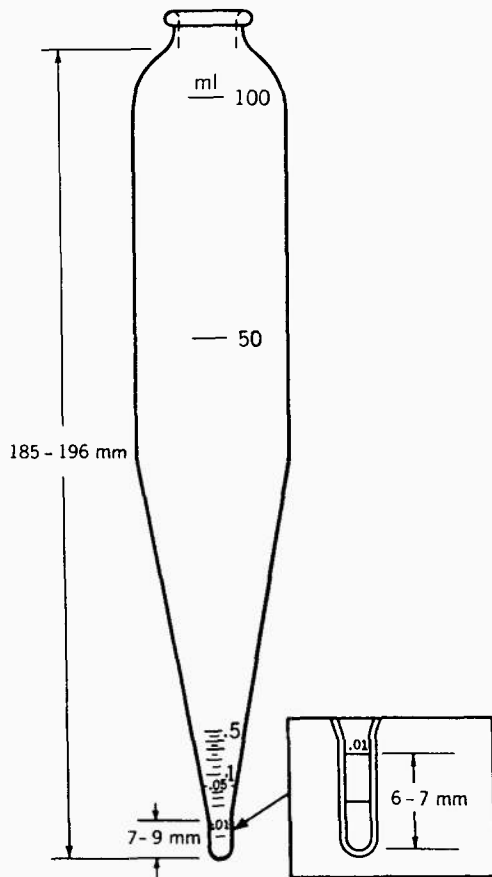


Fig. 3-52. Trace Sediment Test Tube

3-3 LUBRICATION PROPERTIES

3-3.1 GENERAL

A hydraulic fluid should be a good lubricant so that friction and wear in a hydraulic system are reduced to a minimum. The components of a hydraulic system contain many surfaces which are in close contact and which move in such relation to each other that the hydraulic fluid must separate and lubricate. The hydraulic fluid must also be a good wear preventing lubricant. Wear in hydraulic pumps, cylinders, motor controls, valves, and other components can result in increased leakage, loss of pressure, less accurate control, or failure. Protection against wear is often a principal reason for selection of a particular hydraulic fluid since most components of hydraulic systems operate at some time under conditions that can lead to extreme wear, especially during starting and stopping of the system.

Varying degrees of lubrication and wear preventing ability are needed for different systems. The pump design, the system operating temperatures and pressures, component design, and environmental conditions should all be considered when selecting a hydraulic fluid.

Two fundamental and distinct modes of lubrication are generally recognized—hydrodynamic and boundary lubrication. When hydrodynamic conditions exist, a liquid film entirely separates the moving parts. In the boundary condition, contact exists between the mating surfaces. The difference between hydrodynamic and boundary lubrication is clear; however, there is no sharp line of demarcation, but rather a gradual transition between the two.

3-3.2 HYDRODYNAMIC LUBRICATION

Hydrodynamic lubrication is “A system of lubrication in which the shape and relative motion of the sliding surfaces cause the formation of a liquid film having sufficient pressure to separate the surfaces” (Ref. 92). Under ideal hydrodynamic conditions of lubrication, there is essentially no wear since the moving parts do not touch each other. Under these conditions, the parameters of importance are liquid, viscosity, surface speed, and pressure.

Most of the theory of hydrodynamic lubrication is based on the early work of Tower and Reynolds. Full hydrodynamic lubrication offers the significant advantage of low wear rates and low friction. Hydraulic systems should be designed to take full advantage of hydrodynamic lubrication. The coefficient of friction in hydrodynamic lubrication is of the order of 0.001 to 0.010 (Ref. 3).

3-3.3 TRANSITION FROM HYDRODYNAMIC TO BOUNDARY LUBRICATION

A given liquid film between moving parts decreases in thickness as the pressure increases, and/or the liquid viscosity decreases. As the film becomes thinner, a point is reached where the laws of hydrodynamics no longer fully apply since the effects of surface or boundary forces are no longer negligible. As the film becomes still thinner, a state is ultimately reached where metal-to-metal contact occurs. These transitions influence the coefficient of friction as shown in Fig. 3-53. Here, the coefficient of friction is plotted as a function of the dimensionless parameter ZN/p where Z , N , and p are the fluid viscosity, relative surface speed, and pressure, respectively.

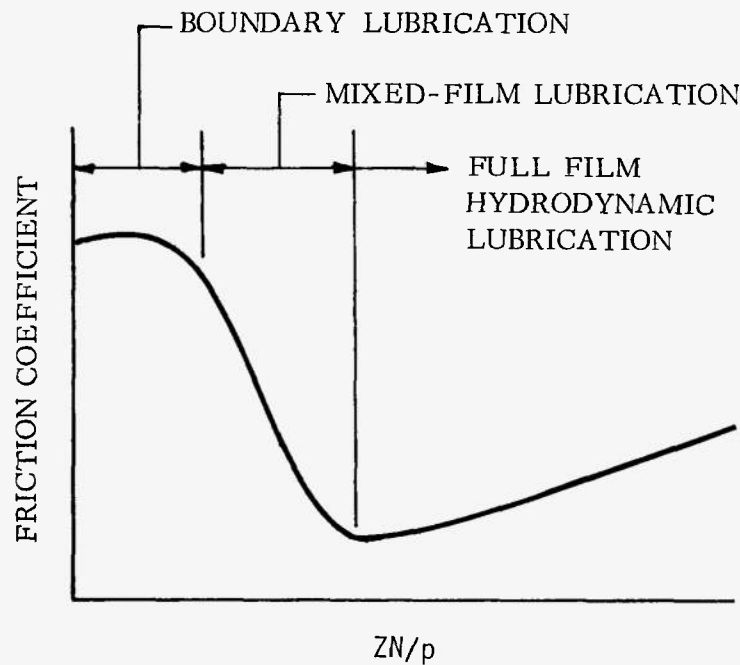


Fig. 3-53. Coefficient of Friction in the Transition from Hydrodynamic to Boundary Lubrication

In the hydrodynamic region, the coefficient of friction is a linear function of ZN/p (see Fig. 3-53). As ZN/p decreases, the film thickness is reduced and the curve begins to deviate from linearity. As ZN/p is decreased further, a point is reached where both boundary and hydrodynamic effects prevail in combination. A further decrease in ZN/p will ultimately rupture the film and the curve will show a sharp break upwards. The minimum point is then regarded as the start of the transition from hydrodynamic to boundary lubrication. There is no sharp line of demarcation, but an intermediate zone where hydrodynamic and boundary effects are both present. This zone is sometimes called the semi-fluid, mixed-film, or quasi-hydrodynamic lubrication zone (Ref. 3).

The condition of full hydrodynamic lubrication is the most desirable; however, all of the factors that make it possible are not always present. Sometimes speeds are so slow or pressures so great that even a very viscous liquid will not prevent metal-to-metal contact. Other cases of stop-and-start operation, reversals of direction, or sharp pressure increases may cause the collapse of any liquid film that had been established. These conditions are not conducive to hydrodynamic lubrication and occur in almost all systems at one time or another.

3-3.4 BOUNDARY LUBRICATION

Boundary lubrication is "A condition of lubrication in which the friction and wear between two surfaces in relative motion is determined by the properties of the surfaces, and by the properties of the lubricant other than viscosity" (Ref. 92). When boundary lubrication exists, the coefficient of friction is independent of both liquid viscosity and sliding velocity. There are different degrees of severity under which boundary lubrication will prevail. Some are only moderate and others are extreme. Blok (Ref. 3) classifies degrees of boundary lubrication on the basis of the mechanical conditions. He lists the following degrees:

(1) Low pressure and low temperature, or mild boundary lubrication as found in low speed sleeve bearings, leaf springs, and hinge joints.

(2) High temperature boundary lubrication as found in cylinders of some steam and internal combustion engines, and in certain high speed sleeve bearings.

(3) High pressure boundary lubrication as generally found in cases involving rolling contact at high pressures but with little frictional or external heat.

(4) High pressure and high temperature, or extreme boundary lubrication, as found in highly loaded hypoid or other gears having high loads and a high degree of sliding friction.

The temperature and pressure at the region of contact are the factors that determine the severity of the boundary lubrication. All types of boundary lubrication are characterized by the rupture of the liquid film and some degree of metal-to-metal contact. The conditions of boundary lubrication should be avoided where possible because of the resulting increase in power consumption, and the high friction and wear that occur.

3-3.5 EXTREME PRESSURE LUBRICATION

Extreme boundary lubrication (par. 3-3.4) in which both temperature and pressure are very high is often referred to as Extreme Pressure, or *EP*, lubrication. *EP* conditions are found in hydraulic systems in pumps, motors, and actuators. *EP* conditions are characterized by welding of portions of mating surfaces, followed by the tearing away of relatively large particles of the metal. A variety of special lubricants with properties tailored to meet the severity of the particular application can frequently be used when *EP* conditions exist. These special properties are generally derived from the various additives contained in the fluid (see Chapter 5), and the net effect is to increase the load-carrying ability of the fluid.

Lubrication when *EP* conditions exist depends upon a combination of mechanical and chemical effects. Part of the lubrication may result from an absorbed film that is present on the two surfaces, and part from additives in the liquid that chemically attack these surfaces where—as a result of high pressure and high sliding velocity—exceedingly high temperatures result. The formation of reaction products then prevents seizure of the moving parts and may reduce friction. The temperature involved may be on the order of 900°F, or higher, so these reactions are often very rapid.

There are various degrees of *EP* conditions and various types of *EP* additives to meet them. The type of additive selected for any particular application will depend on the severity of the boundary conditions. Different types of additives are used for high temperature boundary conditions than for high pressure boundary conditions. A more complete discussion of boundary condition additives is in Chapter 5. Because of the range of conditions through which a system may operate, it is frequently necessary to include more than a single additive, one for the more severe conditions and another for the less severe conditions. Certain disadvantages may result from the use of *EP* additives. Some additives may increase the emulsifiability of the fluid, making it undesirable for applications requiring rapid

separation of fluid and water. Some of the more effective *EP* additives also have a tendency to react with certain structural metals or with some of the synthetic hydraulic fluids.

3-3.6 DEFINITION OF TERMS USED IN DESCRIBING LUBRICATING CHARACTERISTICS

The more common terms used to define the lubricating ability of a liquid are film strength, oiliness, and lubricity. These terms are not precise and a standard of definitions of lubrication, friction, and wear terms recommends that they no longer be used (Ref. 92). However, the terms have been used for many years and do appear in most of the literature pertaining to lubricating characteristics of liquids.

3-3.6.1 Film Strength

Film strength is “The ability of a surface film to resist rupture by the penetration of asperities during sliding or rolling” (Ref. 92). In general, the higher the viscosity, the higher the film strength. A high film strength is primarily inferred from a high load-carrying capacity and is seldom directly measured. It is possible to increase the film strength of a liquid by use of additives.

3-3.6.2 Oiliness

Oiliness is the property of a liquid which causes films of two liquids of identical viscosity to exhibit different coefficients of friction. Oiliness is associated with boundary lubrication and the intermediate zone between boundary and hydrodynamic lubrication. The oiliness of a liquid can be increased by the use of additives. These additives are usually oils of animal or vegetable origin and have certain polar characteristics. A polar molecule has a strong affinity for the metal surface with which it comes in contact and for like molecules. Such a molecule is not easily dislodged from its attachment to the surface. For moderate boundary conditions, damage of sliding parts can be effectively reduced by the use of oiliness agents.

3-3.6.3 Lubricity

Lubricity is the ability of a liquid to impart low friction under boundary conditions. A fluid that forms

a film of low shear strength is said to have good lubricity. Lubricity is a complex function which depends upon liquid oiliness, the extreme pressure and antiwear properties of the liquid, and the properties of the rubbing surfaces.

3-3.7 PREVENTION OF WEAR

The complete elimination of wear is practically impossible. Minimum wear occurs under conditions of hydrodynamic lubrication and maximum wear occurs under conditions of boundary lubrication. However, there are several approaches by which the wear rate under boundary lubrication conditions can be reduced to a satisfactory or controllable level. The main factors which determine the rate of wear can be classified into two basic types—mechanical and lubrication. Proper consideration of these two factors can produce a wear rate which is acceptable.

3-3.7.1 Mechanical Factors

The mechanical factors that affect the wear rate are the choice of materials, the surface finish, and the operating conditions.

Wear can often be reduced by a proper choice of materials for the moving parts. In general, softer materials wear more rapidly than harder materials. There is, however, no direct relationship between hardness and resistance to wear. Materials also differ in their ability to resist the various types of wear. For example, materials selected for their ability to resist abrasion might be more sensitive to corrosion. It is thus necessary to select materials which would resist the most serious type of wear anticipated.

The *combination of metals* used can greatly influence the wear. Some metals are very susceptible to wear when rubbed against themselves, while others are very susceptible to wear when rubbed against different types of metals. In practice, the composition chosen for a given part is influenced by many factors other than wear. Structural strength, weight, cost, and availability may force a compromise between minimum wear and optimum performance.

Surface finish of the mating parts becomes particularly important during break-in or initial wear periods. If one of the two mating surfaces has an initial rough finish, considerable wear may take place. While it is generally desirable to have as smooth a surface as possible, there are instances where surfaces of controlled roughness are desired so that a "wearing-in" or mating

of parts may occur during the initial run-in or break-in period.

Operating conditions of pressure, temperature, and rubbing speed also affect wear. Increased pressure generally reduces film thickness and increases the extent of metal-to-metal contact and wear. High temperature may cause wear due to a decrease in viscosity. Excessive high speeds may result in overheating at local points. Moderate temperatures and pressures are, therefore, preferred from a standpoint of wear. However, optimum conditions for wear may not be the optimum conditions to achieve high efficiency or maximum power from a hydraulic system component.

3-3.7.2 Lubrication Factors

Decreases in viscosity of a system operating under hydrodynamic lubrication will decrease the thickness of the liquid film. If the decrease is sufficient to allow boundary conditions to be reached, metal-to-metal contact occurs and wear increases. Viscosity, therefore, would be expected to have an inverse effect on rate of wear—the greater the viscosity the less would be the expected wear.

Since wear is essentially a phenomenon resulting from friction, it is expected that additives capable of reducing friction under boundary conditions would simultaneously reduce wear. However, there can be instances where there is little or no correlation between friction and wear under boundary lubrication conditions (Ref. 3). Some additives effective in reducing friction have little effect upon wear, while others reduce wear and have little effect upon friction. Lack of correlation is probably due to the fact that wear takes place momentarily in isolated spots whereas friction is normally measured as an average for a larger area and a longer time interval (Ref. 3).

Hydraulic components made from iron alloys other than stainless steel are subject to corrosion unless proper precautions are taken. Most mineral-oil liquids do not have good antirust properties. Although they do offer protection, they must be fortified with appropriate additives if any marked degree of rust prevention has to be achieved (Ref. 3).

3-3.8 TEST METHODS FOR LUBRICATING PROPERTIES

Numerous test methods have been proposed and several have been adopted for evaluating the lubricating and wear reducing properties of fluids. The majority of

these tests have been developed for materials other than hydraulic fluids such as lubricants, greases, and, in some cases, solid lubricants. However, the basic test procedures are adaptable to the evaluation of hydraulic fluids, and several Military Specifications for hydraulic fluids call for these tests or some modification of them.

The test methods fall into three general categories—bench-type tests using nonsimulating test elements, simulated hydraulic systems, and the more elaborate load-carrying and scuffing tests. Standard test procedures, either ASTM or Federal, have been written for some of the test methods.

None of the test methods described in the paragraphs which follow give any indications of the expected “life” of a lubricant or liquid. The engineer or designer is expected to establish proper lubrication procedures and lubricant change intervals. The problems become even more complicated in hydraulic systems because the liquid is both a lubricant and a power transfer fluid. With hydraulic systems operating with sophisticated hydraulic fluids and/or extreme operating conditions, falling back on “accepted practice” can be expensive, either in terms of wasted hydraulic fluids or damaged equipment.

3-3.8.1 Bench-type Friction and Wear Testers

Several bench tests have been developed to measure the lubricating ability of liquids. Each test employs a different type of apparatus that utilizes a unique combination of test elements. The testers are similar in that two well-defined surfaces separated by a liquid film are in motion with respect to each other. The coefficient of friction is usually determined by measuring the restraining force on one of the test elements. Wear is determined by the loss in weight of the parts or by the dimensions of the wear scar. Boundary lubrication characteristics are determined by increasing the load on the surfaces until seizure occurs.

Because of their differences, the various bench testers do not necessarily rate a given series of liquids in the same order, and results from a single test procedure can be misleading. Also, the results obtained do not always correlate well with actual operation. In many instances, the results of several different bench tests may be taken as a whole in determining the lubricating ability of a given hydraulic fluid. Experience has shown that application of most of these test procedures will separate those hydraulic fluids which are extremely poor lubricants from those which are potentially good lubricants.

Five of the more commonly used bench-type testers and their test methods are described in the paragraphs which follow.

3-3.8.1.1 Timken Tester

Test Method: Federal Test Method 6505 (Ref. 93)

In the Timken test, a steel block is pressed against a rotating, cylindrical steel ring (see Fig. 3-54(A)). The test is run for 10 min at a rubbing speed of 400 ft/sec. The liquid is allowed to flow over the test pieces. In starting a test, the motor is brought up to speed and a load is placed on the steel rub shoe block by means of a weight and lever system. The test can be conducted as a wear test by running at a set load until failure or as an *EP*- or load-carrying test by increasing the load until failure. Federal Test Method 6505 (Ref. 93) calls for the test to be conducted as a load-carrying test. Failure is indicated by scoring on the test block or test ring. The results are reported as the load (determined from the scar dimensions and the load) applied just prior to scoring or pickup of metal.

3-3.8.1.2 Almen Tester

In the Almen test, a cylindrical rod is rotated in a split bushing which is pressed against it (see Fig. 3-54(B)). Frictional force is measured by a restraining force on the split bushing. Two versions of the Almen test are conducted—the Almen *EP* test and the Almen wear test.

In the Almen *EP* test, the machine is run without an applied load for 30 sec as a break-in period. Weights are added every 10 sec in multiples of 2 lb until failure occurs as indicated by seizure or sudden increase in torque. Test results are expressed as the torque and load which causes seizure.

In the Almen wear test, the machine is run without an applied load for 30 sec as a break-in period. Four 2-lb weights are added at 10-sec intervals. Operation is continued for 20 min. Total weight loss of the journal and the bushings in mg is determined, and is reported as the wear.

3-3.8.1.3 Falex Tester

Test Methods: Federal Test Method 3807 (Ref. 94)

Federal Test Method 3812 (Ref. 95)

In the Falex test a cylindrical rod is rotated between two hard V-shaped bearing blocks which are pressed against the rod (see Fig. 3-54(C)). Friction torque is continuously monitored. Both the journal and the V blocks are submerged in the liquid under test. The two Federal Test Methods referenced above utilize the Falex Tester in the evaluation of solid film lubricants.

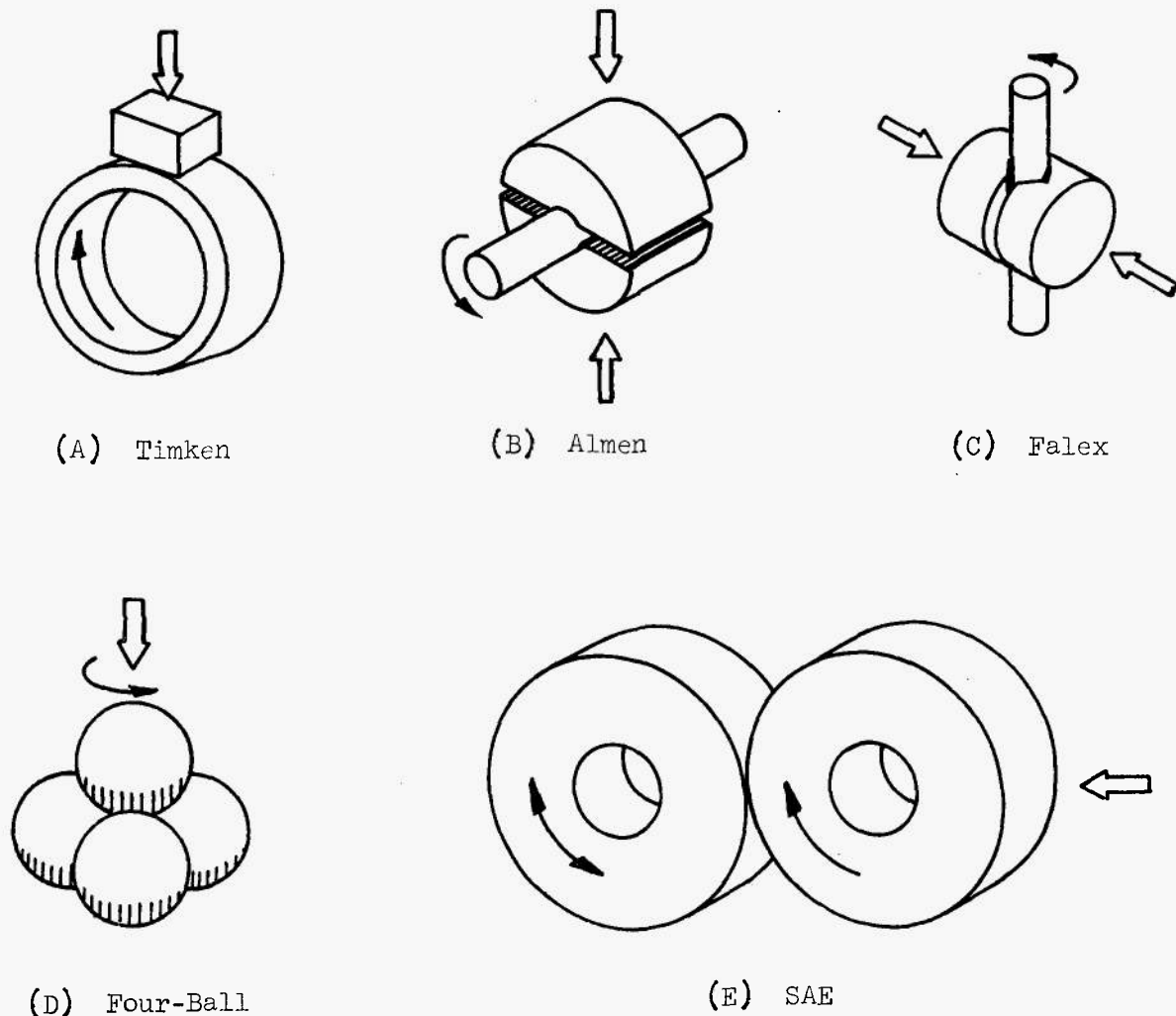


Fig. 3-54. Five Bench-type Friction and Wear Testers

However, the basic procedures of the two tests are adaptable to the evaluation of liquids. The test can be run in two ways—as a wear test and a load carrying test.

For wear testing, the machine is run at a specified load for a specified time. The amount of wear is determined as the amount of adjustment that must be made in the loading system to maintain the desired load.

For the *EP* test, the load is increased continuously until seizure occurs. The test begins with a break-in period for 3 min at 300 lb load. The load is then increased to 500 lb and held for 1 min and then increased in 250-lb increments with a 1-min run until failure occurs. Results are expressed in pounds load at seizure.

3-3.8.1.4 Four-ball Tester

Test Methods: ASTM D-2596-67T (Ref. 96)
Federal Test Method 6514 (Ref. 97)
ASTM D-2266-64T (Ref. 98)

In the four-ball machine (often called the “Shell” Four-ball Tester) a 1/2-in.-diameter steel ball is rotated in contact with three stationary similar balls which are clamped in a fixed position (see Fig. 3-54(D)). The rubbing surfaces are submerged in the liquid to be tested. The test can be operated as a wear test or an *EP* test.

For a wear test, the machine is operated at a specified temperature, load, and speed, with balls of given material. Federal Test Method 6514 (Ref. 97) and ASTM D-2226-64T (Ref. 98) are used for determining the wear characteristics of lubricating greases with the four-ball tester. The general procedures are adaptable to hydraulic fluids as well as greases. They call for test conditions of 1,200 rpm, a load of 40 kg, a test temperature of 167°F (75°C), and a test time of 60 min. At the end of the test, the scar diameter on the lower three balls is measured under a microscope. The average diameter in millimeters is reported and is a measure of wear under the specified conditions.

For the *EP* test (ASTM D-2596-67T (Ref. 96)) there is no provision for temperature control, and the test is started at room temperature. A test run of 10-sec duration at a given load is usually made. Scar diameters are measured and the Hertzian contact stresses are calculated. The load is increased in increments, and the process is repeated until welding occurs. This load is called the weld point or weld load.

Many variations on the four-ball wear and *EP* tests are used. Many liquid specifications call for a four-ball test as specified or with certain changes made in the test time, load, speed, or temperature.

3-3.8.1.5 SAE Tester

Test Method: Federal Test Method 6501 (Ref. 99)

In the SAE machine (see Fig. 3-54(E)), two cylinders aligned axially and in contact with each other are driven at different speeds. One of the cylinders may be driven in either direction. The pieces revolve under a flooded lubrication condition from the test liquid held in a cup. The load pressing the cylinders together can be increased until failure occurs. This machine differs from the four-ball tester in that a combination of rolling and sliding friction is involved. The ratio of sliding to rolling can be changed by varying the relative speed of the two cylinders.

Federal Test Method 6501 (Ref. 99) is a test procedure for determining the load-carrying capacity of gear lubricants using the SAE tester. The same test procedures, however, are adaptable to any liquid lubricant or to hydraulic fluids. The machine is started and operated at a light load for a 30-sec break-in period. The automatic loading device then increases the load steadily until scoring occurs. The results are expressed in terms of the average load needed to cause scoring based on three repeat tests.

3-3.8.2 Evaluation of Lubricating Properties by Pump Tests

None of the bench tests gives accurate or complete correlation with the operation of hydraulic fluids in a hydraulic system. The final test of the lubricating characteristics of any hydraulic fluid is its actual performance in a hydraulic system. The hydraulic pump is usually the most critical unit as far as lubricating characteristics of the hydraulic system are concerned; therefore, pump tests have been developed and widely accepted for studying lubricating properties of hydraulic fluids.

Pump tests normally involve the simplest hydraulic circuit possible: a pump; a means of maintaining system pressure such as a relief valve; a reservoir; a heat exchanger; and various instruments for measuring speed, pressure, temperature, and flow rate. The test is usually run for a specified period of time with a given pump. Critical parts of the pump are examined before and after testing, and the amount of wear determined by changes in dimension or changes in weight.

In addition to data on the lubricating properties of hydraulic fluids, pump tests provide data on the overall performance of the pump system, and the functional ability of the hydraulic fluid. Other benefits gained include: actual determination of wear in a simulated system; information on liquid stability; effects of seals and packings, corrosion, sludging; and the heat and power transfer qualities of the liquid under controlled conditions (Ref. 4).

Several pump tests have been described in the literature. All types of pumps have been used, and test conditions have been widely varied. Some pump tests have been developed specifically for shear stability evaluation (see par. 3-2.5.3), but will still provide data on the lubricating properties of the liquid. A few of the pump tests have been written into formal test procedures and are discussed in the paragraphs which follow.

3-3.8.2.1 Simulative Recirculating Pump Test

Test Method: ASTM D-2428-66T (Ref. 100)

This test method covers a procedure for system evaluation of aerospace hydraulic fluids. The method recommends a typical test system geometry, data to be obtained, and control of test variables and procedures to assure a uniform approach of liquid screening and evaluation. Recommendations concerning specific hardware and rigid techniques have been avoided where possible to allow the general method to be used as the state-of-the-art advances. Since the method was

purposely generalized, it is important that specified data be taken in order that valid comparisons of test results of various liquid can be made. The method consists of recirculative pumping of the test liquid through a system that closely simulates the final system in which the liquid will be used. Wear and lubricating properties of the liquid are determined from evaluation of critical parts of the system before and after the test. This test procedure, however, is not primarily intended for wear and lubrication testing, but rather for liquid functional suitability.

3-3.8.2.2 *Pump Loop Wear Test*

Test Method: ASTM D-2271-66 (Ref. 101)

This test method describes a procedure for measuring the wear characteristics of hydraulic fluids for use in industrial applications. A fixed volume of the hydraulic fluid is circulated through a pump rig under standard conditions of time, pressure, and temperature for 1,000 hours. Differences in weight of the pump parts at the start and finish of the test are reported along with the total percent loss.

3-3.8.3 **Other Lubricating Characteristics Tests**

Numerous other tests for evaluating the lubricating properties of lubricants have been developed. Several of the procedures that concentrate on the load-carrying ability of liquids have been written into formal test procedures. These test standards are not primarily intended for the evaluation of hydraulic fluids, but mention of them is made here since they have been used to screen potential hydraulic fluids. They are now being used more frequently, and the trend toward more severe operating conditions in aircraft often leads to the use of the same liquid as lubricant and hydraulic fluid. The lubricating properties of the liquid then become extremely important.

3-3.8.3.1 *Load-carrying Ability of Lubricating Oils at 400°F*

Test Method: Federal Test Method 6511 (Ref. 102)

This method describes a procedure for determining the load-carrying ability of lubricating oils at 400°F with respect to gears.

Two special test gears are mounted in a WADD High-temperature Gear Machine adapted to a modified

Ryder Gear-Erdco Universal Drive System. The test oil is heated to 400°F and the gears rotated at 10,000 rpm in cycles of 10 min with uniform increases in gear load for each cycle. The gears are examined for scuffing at the end of each cycle. The cycles are continued until a set percentage of gear tooth face scuffing is observed. The load-carrying ability is that gear tooth load which produces an average gear tooth scuffing of 22.5 percent. Results are reported as the percent of load-carrying capacity of the test oil to a reference oil.

3-3.8.3.2 *Load-carrying Capacity of Steam Turbine Oils*

Test Method: ASTM D-1947-66 (Ref. 103)

This test method is almost the same as the one described in par. 3-3.8.3.1. The exceptions are that it is limited to steam-turbine oils and is conducted without heating the test liquid.

3-3.8.3.3 *Gear Fatigue Characteristics of Aircraft Gas Turbine Lubricants at 400°F*

Test Method: Federal Test Method 6509 (Ref. 104)

This method describes a procedure for determining the fatigue characteristics of aircraft gas turbine engine lubricants at 400°F with respect to gears.

Two special test gears are mounted in a WADD High-temperature Gear Machine adapted to a modified Ryder Gear-Erdco Universal Drive System. The test oil is heated to 400°F and the gears rotated at 10,000 rpm in 10 min cycles with uniform increases in load at each cycle. At the end of each cycle the gears are examined for scuffing. When a predetermined maximum load is reached, the cycle duration is increased to 2 hr at constant load. At the end of each cycle, the gears are then observed for development of fatigue pits which are large enough to be readily discernible to the eye.

Results are reported as the percent of load-carrying ability, with respect to a reference oil, of the test oil and the rating of each fatigue cycle in terms of the number of fatigue pits.

3-3.8.3.4 *Load-carrying Ability of Lubricating Oils (Ryder Gear Machine)*

Test Method: Federal Test Method 6508 (Ref. 105)

This method describes a procedure for determining the load-carrying ability of lubricating oils with respect to gears.

Two special test gears are mounted in a Ryder Gear-Erdco Universal Tester. The test oil is heated to 165°F and the gears rotated at 10,000 rpm in cycles of 10 min each with uniform increases in gear load for each cycle. The gears are examined for scuffing at the end of each cycle. The cycles are continued until a preset percent of gear tooth scuffing is observed. The load-carrying ability is that gear tooth load which produces an average gear tooth scuffing of 22.5 percent. Results are reported as the percent of load-carrying ability of the test oil to a reference oil.

Precision:

- (a) Repeatability. Relative readings should not differ from their mean by more than 10 percent.
- (b) Reproducibility. Relative readings should not differ from their mean by more than 5 percent.

3-4 CHEMICAL PROPERTIES

3-4.1 CHEMICAL STABILITY

Most hydraulic fluids are complex mixtures which are affected by temperature, pressure, atmospheric conditions, moisture, metals in the hydraulic system, mechanical shear, and other external influences. These influences define the operating conditions of the hydraulic system, and a hydraulic fluid should be stable under the imposed conditions. Any or all of these influences can change the properties of the hydraulic fluid to such an extent that it may be unsuitable for use in the system for which it was intended. However, it is mandatory that the system be operated with a hydraulic fluid that does not suffer degradation or that changes only to such an extent that its operating ability is not significantly impaired within a defined range of use conditions.

The stability of many types of hydraulic fluids has been extensively studied under a wide variety of conditions in the laboratory. Oxidation, thermal stress, hydrolysis, radiation, and mechanical stress due to shear and cavitation are the primary forces that tend to alter the chemical nature of hydraulic fluids. Stresses due to shear are discussed in par. 3-2.5. Cavitation is discussed in par. 3-6.1.2.

Because of the wide variety of fluid stability data available in the literature, examples of specific hydraulic fluids will be avoided in this discussion. Instead, relative comparisons will be made of the various chemical classes of hydraulic fluids currently available or under development. For additional details, the specific references should be consulted.

One of the most difficult aspects of determining stability involves the selection of criteria of change. All hydraulic fluids can and will undergo changes in their properties during use. Some of these changes affect the functional ability of the fluid; some affect the chemical composition; some affect the thermal properties; etc. Some changes may be harmful while others may have no effect on the performance of the hydraulic fluid. For example, changes in color indicate a change in the liquid; however, such a change will not normally affect the functional ability of the liquid. On the other hand, an increase in acid content might result in a hydraulic fluid too corrosive for further use, or the viscosity may change so that the hydraulic fluid no longer performs its function. Obviously then, some properties have much more meaning in terms of hydraulic fluid stability than others. Even then, the conditions to which the hydraulic fluid will be subjected determine which properties are the critical ones and are most desirable to maintain as stable as possible.

If a liquid encounters one or more of the stresses or forces previously mentioned, the result is generally a change in one or more of the following: viscosity, formation of volatile components, formation of insoluble materials, or formation of corrosive products. Insolubles formed may range in nature from hard particles to sludges and gums. Corrosion products generally form as the result of thermal or oxidative decomposition, or from hydrolysis. Volatile components can form as the result of oxidative, thermal, or radiation effects. All of these changes are usually undesirable, and precautions should be taken to avoid them or reduce their effects.

The stability of a hydraulic fluid is also affected by the metals used in the system. Depending on the chemical type of the liquid, certain metals can act as catalysts in the deterioration process. The problem is essentially a question of compatibility of the hydraulic fluid and the metals of construction (see par. 3-6.1).

3-4.2 OXIDATION STABILITY

Oxidation stability refers to the ability of a liquid to resist reaction with oxygen or oxygen-containing compounds, and is an important factor that affects storage life of hydraulic fluids and performance life of hydraulic fluids used in open systems (noninerted). Oxidation results in liquid deterioration and is manifested by changes in certain physical and chemical characteristics of the lubricant—such as viscosity, precipitation of insolubles, lacquer and varnish formation, acidity, and corrosiveness. When the concentration of oxidation products reaches a critical value, depending upon the

application, the hydraulic fluid will no longer perform satisfactorily. Many of the newer hydraulic systems reduce the damage from oxidation by using systems that are inerted.

Oxidation rates of most types of liquids are temperature sensitive. Degradation products increase with increasing temperature and, as a result, require more frequent hydraulic fluid replacements. The oxidation rate is also usually increased with increases in the amount of air and water contamination; and the presence of metallic particles, dirt, and dust. In addition, for petroleum liquids the type of crude oil from which the liquid is derived, as well as the refining methods, may also affect the oxidation rate.

The oxygen necessary for the oxidation reaction usually results from the presence of air contamination in the liquid or exposure to air in open systems. In order to retain useful hydraulic fluid life at higher temperatures, systems must exclude air, and the hydraulic fluid must be substantially free of dissolved air prior to charging the system. The use of antioxidants can substantially improve the oxidation stability of a liquid. Practically all commercial hydraulic fluids are stabilized by antioxidants.

Thermal and/or oxidative stability are generally the factors that limit the upper operating temperature of the hydraulic fluids, depending upon the systems in which the hydraulic fluids are used. Most petroleum base hydraulic fluids are limited to less than 200°F operation in open systems while some are capable of 550°F operation in closed inerted systems. The maximum useful temperatures and the oxidation resistance of several types of hydraulic fluids are given in Tables 3-7 and 3-8. The oxidation resistance ratings shown in Table 3-8 are for operation below the recommended long duration operating temperatures of Table 3-7. The polyphenyl ethers and the silicones are the most stable liquids at the higher temperatures. However, most types of liquids are relatively poor lubricants in comparison with petroleum-base liquids.

Oxidation stability is an important factor in the prediction of the performance of a hydraulic fluid in an oxidizing environment. Without adequate oxidation stability, the life of a liquid may be extremely limited and unless the liquid is frequently replaced, there is a serious possibility of damage to lubricated parts. Oxidation stability becomes a prime requisite of liquids serving in closed uninerted lubrication systems such as hydraulic systems where the oil is recirculated for extended periods. There are some instances where con-

trolled amounts of oxidation are beneficial. For example, on certain metals, the presence of oxide films determines the ability of the metal to be lubricated and prevent surface welding and galling. Complete removal of oxygen from systems containing such metals may cause problems when the oxide surface films revert to bare metals (Ref. 106). This possibility is usually taken care of by use of additives such as tricresyl phosphate.

3-4.3 THERMAL STABILITY

Thermal stability is the ability of a liquid to resist decomposition by temperature only. It determines the ultimate temperature limit of service for a hydraulic fluid. As design temperatures of new hydraulic equipment continue to rise, the thermal stability of lubricants and hydraulic fluids becomes increasingly important. Much research in recent years has resulted in a number of candidate hydraulic fluids which can operate for long periods at relatively high temperatures. Sustained high temperature stability of a hydraulic fluid is a necessary characteristic. Ideally, a hydraulic fluid should not degrade significantly between normal system overhauls.

Table 3-9 presents the deterioration temperatures for the same fluids discussed in par. 3-4.2. The polyphenyl ethers and the silicones have high deterioration temperatures (in excess of 600°F). However, the super refined mineral oils and synthetic hydrocarbons have deterioration temperatures almost as high and are better lubricants. The data presented in Table 3-9 are approximate only and vary depending on the conditions the tests are conducted under. For example, many nonhydrocarbon liquids are less stable in the presence of ferrous metals than other metals.

Measurement of thermal stability has not previously been standardized, but the usual procedure was to relate it to change in weight of the liquid sample, development of acidity, formation of insolubles, or changes in other properties such as color, viscosity, pour point, flash and fire points, etc. (Ref. 106). ASTM D-2160-66 (see par. 3-4.6.3.2) is now being used commonly as a standard test method for thermal stability of hydraulic fluids. Various other laboratory and bench scale tests have been developed, which usually involve heating the liquid and measuring changes in the properties. If the container holding the liquid is open to the air, the test then becomes a combination oxidation and thermal stability test. In order to separate thermal and oxidative effects, test procedures have been devised in which oxygen is removed from the system and replaced by an inert gas such as nitrogen or helium. These purely thermal stability tests are carried out in sealed systems. The

TABLE 3-7.
MAXIMUM OPERATING TEMPERATURE OF HYDRAULIC FLUIDS^a

Hydraulic Fluid Type	Approximate Upper Use Limit, °F		
	Long Duration (500-1000 hr)	Moderate Duration (10-100 hr)	Hot Spot Short Duration (< 1 hr)
Mineral Oils	275	300	350
Emulsions			
Water-glycols	200	---	---
Alkyl Phosphates	225 ^b	---	---
Super-refined Mineral Oils, Synthetic Hydrocarbons	300-450 ^b	550	700
Silanes	---	---	---
Polyglycols	325-350	375-400	450-500
Dibasic Acid Esters	350	400	425
Neopentyl-polyol Esters	375	425	550
Silicate Esters	375-400	475-525	575
Aromatic Phosphate Esters	200	400	575
Halogenated Aromatics	450	575	600
Silicones	425-550 ^c	550-625	800
Polyphenyl Ethers	500	600-700	900
Fluorinated Alkyl Ethers	500	600	800

^a Temperature limits depend on the type of pump used such as gear, vane, piston, etc.

^b Depending on oxidation resistance

^c Range due to many viscosities available

— No reliable data

liquid and container are placed in a chamber which is evacuated and then filled, using nitrogen or other inert gas. This procedure is repeated until little, if any, oxygen remains in contact with or is dissolved in the test liquid. Containers are then heated for a given period of time and the change in the liquid measured.

It is best to determine the thermal stability in an operating system similar to that for which the hydraulic fluid is intended. Pump-loop tests have been devised which can be operated for extended periods at elevated temperatures, but they are often impractical because of size and expense. The sealed bomb tests are then often used because test conditions of interest nearly duplicate those in hydraulic systems.

3-4.4 HYDROLYTIC STABILITY

Hydrolytic stability refers to the ability of hydraulic fluids to resist reaction with water. Undesirable forma-

tions of solids or acidic and corrosive materials may result, or a stable water and oil emulsion which degrades lubricating ability and promotes rusting and corrosion may form.

Since it is rarely possible to completely exclude moisture from any lubricant or hydraulic system, hydrolytic stability is an important requirement of fluids. It affects the life of liquids both in the original storage containers and in the hydraulic system. In storage, moisture may come in contact with a hydraulic fluid if storage drums are not properly sealed. Within the hydraulic system, temperature changes will cause reservoir breathing and condensation of moisture during shut-down periods. Even in supposedly "sealed" systems, moisture is difficult to exclude because of seals, fittings, and other possible leakage points.

Until the advent of synthetic liquids, little consideration was given to hydrolytic stability because of the

TABLE 3-8.
OXIDATION AND VARNISHING RESISTANCE OF HYDRAULIC FLUIDS

Hydraulic Fluid Type	Resistance to Oxidation	Tendency to Form Solids or Varnish
Mineral Oils	Good	---
Water-in-mineral Oil Emulsions	Good	---
Water-glycols	Good	---
Alkyl Phosphates	Good	---
Super Refined Mineral Oils, Synthetic Hydrocarbons, and Silanes	Fair to good	Large
Polyglycols	Fair	Small to medium
Dibasic Acid Esters	Good	Large
Neopentyl-polyol Esters	Good	Large
Silicate Esters	Fair to good	Small to medium
Aromatic Phosphate Esters	Good	Medium
Halogenated Aromatics	Excellent to 500°F	Small
Silicones	Excellent to 400°F Good above 400°F	Small
Polyphenyl Ethers	Excellent to 500°F	Small

— No reliable data

[From: F. D. Yeaple, *Hydraulic and Pneumatic Power and Control*⁵⁸. Used by permission of McGraw-Hill, Inc.]

outstanding hydrolytic stability of petroleum oils. However, stability of synthetic fluids and of some additives in hydraulic fluid formulations must be considered. Table 3-10 presents data on the relative hydrolytic stability of several classes of hydraulic fluids. The most moisture-sensitive of these hydraulic fluids are the silicate esters. Hydrolysis of these fluids produces a silicate sludge which readily clogs filters, servo valves, and capillary passages. Great care is needed to insure that no water is present in the system prior to charging with this type of fluid.

3-4.5 RADIATION RESISTANCE

It has only been since the early 1950's that the radiation resistance of hydraulic fluids has become important. In the design of modern weapon systems, aircraft, and mechanical devices, hydraulic systems are frequently expected to be exposed to nuclear radiation. Of all system components, the hydraulic fluid is the most

susceptible to damage by radiation. Since conventionally used hydraulic fluids and lubricants are especially susceptible, the effects of radiation on their performance should be considered in the design of almost all systems. However, there is no general requirement for radiation resistance in most hydraulic fluid specifications.

Considerable basic work has been done on the radiation of simple organic structures. With the more complicated molecular structures characteristic of lubricants, both petroleum and synthetic, it has not been feasible to make studies of the precise reactions that occur. The empirical observations are: (Ref. 107) (a) viscosity may at first be decreased, but eventually increases, (b) acidity increases, (c) volatility increases, (d) foaming tendencies increase, (e) coking tendencies generally increase but occasionally decrease, (f) flash points decrease, (g) autogeneous ignition temperatures decrease, and (h) oxidation stability decreases.

In addition to the listed changes in physical and chemical properties, gas is always liberated (Ref. 107).

TABLE 3-9.
DETERIORATION TEMPERATURE OF
HYDRAULIC FLUIDS

Hydraulic Fluid Type	Incipient Thermal Degradation Temperature °F
Super-refined Mineral Oils, Synthetic Hydrocarbons, and Silanes	600-700
Polyglycols	500-550
Dibasic Acid Esters	525
Neopentyl-polyol Esters	575
Silicate Esters	550-600
Aromatic Phosphate Esters	500-600
Halogenated Aromatics	600-650
Silicones	625-800
Polyphenyl Ethers	750-850

[From: F. D. Yeaple, *Hydraulic and Pneumatic Power and Control*⁵⁸. Used by permission of McGraw-Hill, Inc.]

For petroleum liquids the gases are frequently hydrogen and methane. The remaining products of decomposition are frequently gels that tend to clog hydraulic systems. The formation of the gases and gels presents a difficult design problem, and provisions must be made in the system for their presence.

Although some changes in lubricants have been found after radiation doses of 10^7 roentgens,² the major effects are observed between 10^8 and 10^9 roentgens (Refs. 107, 108). Beyond 10^9 roentgens most liquid lubricants have been damaged to the extent that they are completely unserviceable.

In general, petroleum lubricants are more resistant to radiation damage than other lubricants. An exception is the polyphenyl ether family which is very resistant to damage. Currently, the silicone liquids exhibit the poorest radiation resistance of all the high temperature liquids (Ref. 4). Inclusion of atoms other than carbon, hydrogen, and oxygen in the molecule generally reduces radiation resistance. Table 3-11 presents data on the relative radiation resistance of various hydraulic fluids.

² 1 roentgen = absorption of 93 ergs/g water or 83 ergs/g air.
1 rad = 100 ergs/g.

TABLE 3-10.
HYDROLYTIC STABILITY OF
HYDRAULIC FLUIDS

Hydraulic Fluid Type	Comparative Rating
Super-refined Mineral Oils, Synthetic Hydrocarbons, and Silanes	Excellent
Polyglycols	Good
Dibasic Acid Esters	Fair
Neopentyl-polyol Esters	Fair
Silicate Esters	Poor to Fair
Aromatic Phosphate Esters	Fair to Good
Halogenated Aromatics	Excellent
Silicones	Excellent
Polyphenyl Ethers	Excellent

[From: F. D. Yeaple, *Hydraulic and Pneumatic Power and Control*⁵⁸. Used by permission of McGraw-Hill, Inc.]

Considerable work has been done on the repression of radiation damage to organic liquids by additives. The presence of additives such as antioxidants and foam inhibitors may offer a slight repression of the effects of radiation.

3-4.6 CHEMICAL STABILITY TESTS

A large number of tests to determine the chemical stability of hydraulic fluids have been proposed and developed. Their number and variety are almost overwhelming. Some tests are comprehensive in that they evaluate the overall stability of the liquid over a wide range of conditions. Others are very narrow in their scope in that they evaluate the stability of one property of the liquid over a more limited range of conditions. All of the tests, however, are of two basic modes of operation: (1) tests which measure changes in selected properties of the liquid before and after exposure to controlled conditions, and (2) tests which measure the effects of the liquid on a controlled system component or test specimen. Examples of the latter type are pump-loop tests which measure the effect of liquids on the pump, and oxidation-corrosion tests which measure the changes in metals exposed to the liquids.

TABLE 3-11 .
RADIATION RESISTANCE
OF HYDRAULIC FLUIDS

Fluid Type	Relative Radiation Resistance
Mineral Oils: MIL-H-5606 MIL-L-25598	Poor Low
Super-refined Mineral Oils: Naphthenic and Paraffinic	Poor
Synthetic Hydrocarbons (Average)	Poor
Diesters: MIL-L-7808C	Poor
Triesters: MIL-L-9236B	Poor
Silicate Esters	Poor
Disiloxane-dieters: MLO-8515	Poor
Disiloxane: MLO-8200	Poor
Polysiloxanes	Poor
Chlorinated Silicones	Poor
Silicone Ester Blends: MLO-5998	Poor
Phosphate Esters	Poor
Polyphenyl Ethers	Excellent

[From: C. Spar, *Hydraulic Fluids and Their Applications*¹⁴⁰. Used by permission of ASME.]

Since there is a wide variety of tests, only a few of the more widely accepted procedures will be discussed here. These tests can be divided into five areas of application: general indicators of liquid stability, oxidation stability tests, thermal stability tests, hydrolytic stability tests, and radiation resistance tests. The inclusion of a test in one particular category does not mean it is limited entirely to that category—only that its predominant use is in that general area.

3-4.6.1 Indicators of Liquid Stability

A large number of the tests for liquid stability consist of determining the values of various properties of the liquid, subjecting the liquid to controlled test conditions, and then measuring the changes in the selected properties. Those properties most often used as indicators of changes in liquid stability are: color, viscosity, flash and fire points, neutralization number, carbon residue, precipitation number, and ash content. The viscosity and the neutralization number are the most

commonly used indicators. Viscosity test methods have been described in par. 3-2.1.11. Flash and fire points have been discussed in par. 3-2.7.1.1. Details of the test methods for precipitation number and ash content can be found in the ASTM Test Methods (Refs. 109, 110).

3-4.6.1.1 Color

Test Methods: Federal Test Method 102.6 (Ref. 111)
ASTM D-1500-64 (Ref. 112)

This method describes a procedure for the visual determination of the color of a wide variety of petroleum products such as lubricating oils, heating oils, diesel fuel oils, and petroleum waxes. While the color of a hydraulic fluid may have no correlation with its functional ability, a change in color generally does indicate a change in the fluid and can be used as an indicator of possible stability changes.

A measured sample of the test fluid (diluted with kerosene when samples are darker than ASTM Color No. 8) is placed in a standard glass sample jar in a colorimeter, and its color is compared to the color of standard glass panels. The color of the sample is reported as the number of the next darkest glass standard.

Precision: The data which follow should be used for judging the acceptability of results. Results should not be considered suspect unless they differ by more than the following amounts:

- (a) Repeatability. 0.5 color unit
- (b) Reproducibility. 0.5 color unit

3-4.6.1.2 Neutralization Number

Test Methods: ASTM D-664-58 (Ref. 113)
ASTM D-974-64 (Ref. 114)

Changes in acidity or alkalinity are often used as measures of the deterioration of liquids, particularly in stability tests for oxidation and corrosion. Oxidation of most organic materials can result in the formation of acidic compounds.

The term "neutralization number" is often used in expressing an acidity or alkalinity of lubricating liquids and hydraulic fluids. It is defined as the number of milligrams of potassium hydroxide required to neutralize all the acids present in one gram of the sample, or the equivalent (in milligrams of potassium hydroxide) number of milligrams of hydrochloric acid required to neutralize all of the bases present in one gram of the sample. The neutralization number is a general term that can refer to the results of different tests so the test method and the pH of the final solution must be specified.

Two widely accepted test procedures for determining the neutralization number of liquids have been developed. The methods were developed primarily for petroleum base materials, and they give fictitious results with certain synthetic materials used as hydraulic fluids, i.e., the results may actually indicate the saponification of an ester, excessive hydrolysis of additives, etc. It is suggested that the test method recommended by the manufacturer of a synthetic liquid be used to indicate changes which have occurred in a particular synthetic liquid.

(1) *Neutralization Number by Potentiometric Titration (ASTM D-664-58 (Ref. 113))*:

This method describes the procedure for the determination of acidic or basic constituents in petroleum products and lubricants. The method resolves these constituents into groups having weak acid, strong acid, weak base, and strong base ionization properties, provided the dissociation constants of the more strongly acidic or basic compounds are at least 1,000 times that of the next weaker groups. In new and used liquids, the constituents that may be considered to have acidic characteristics include organic and inorganic acids, esters, phenolic compounds, lactones, resins, salts of heavy metals, salts of ammonia and other weak bases, acid salts of polybasic acid, and additional agents such as inhibitors and detergents. Constituents that may be considered to have basic properties include organic and inorganic bases, amino compounds, salts of weak acids, basic salts of polyacidic bases, salts of heavy metals, and additional agents such as inhibitors and detergents.

To determine neutralization numbers by this method, the sample is dissolved in a mixture of toluene and isopropyl alcohol containing a small amount of water. It is then titrated potentiometrically with alcoholic potassium hydroxide or hydrochloric acid solution using a glass indicating electrode and a calomel reference electrode. The potentiometer meter readings are plotted against the respective volumes of titrating solutions, and the end points for each acid or base group are taken at inflections in the resulting curve. When no definite inflections are obtained, end points are taken at meter readings corresponding to those found for standard nonaqueous acidic and basic buffer solutions.

Definition of the terms used to designate the various measured values are:

- (a) *Total acid number*. The quantity of base expressed in milligrams of potassium hydroxide that is required to neutralize all acidic constituents present in one gram of sample.
- (b) *Strong acid number*. The quantity of base expressed in milligrams of potassium hydroxide

that is required to neutralize the strong acid constituents present in one gram of sample.

- (c) *Total base number*. The quantity of acid expressed in terms of the equivalent number of milligrams of potassium hydroxide that is required to neutralize all basic constituents present in one gram of sample.
- (d) *Strong base number*. The quantity of acid expressed in terms of the equivalent number of milligrams of potassium hydroxide that is required to neutralize the strong base constituents present in one gram of sample.

The results are reported as the total acid number, strong acid number, total base number, and strong base number.

(2) *Neutralization Number by Color-indicator Titration (ASTM D-974-64 (Ref. 114))*.

This method is intended for the determination of acidic or basic constituents in petroleum products and lubricants, which are soluble in mixtures of toluene and isopropyl alcohol. It is applicable for the determination of acids or bases which have dissociation constants in water larger than 10^{-5} . Extremely weak acids or bases having dissociation constants smaller than 10^{-9} do not interfere. Salts react if their hydrolysis constants are larger than 10^{-9} .

To determine the total acid or strong base number, the sample is dissolved in a mixture of toluene and isopropyl alcohol containing a small amount of water, and the resulting single phase solution is titrated at room temperature with standard alcoholic base, or alcoholic acid solution, respectively, to the end point indicated by the color change of the added p-naphthol-benzene solution (orange in acid and green-brown in base). To determine the strong acid number, a separate portion of the sample is extracted with hot water and the aqueous extract is titrated with potassium hydroxide solution using methyl orange as an indicator. Definitions of the terms total acid number, strong acid number, and strong base number are given in par. 3-4.6.1.2(1).

The acid or base number is calculated and reported as the number of milligrams of potassium hydroxide to neutralize one gram of the sample and is identified by the notation ASTM D-974-64 (Ref. 114).

3-4.6.1.3 Carbon Residue

The carbon residue left after evaporation and pyrolysis of a liquid can give some indication of the relative coke-forming properties of the liquid. The methods presented were originally intended for the study of fuel

oils and motor oils that came in contact with extremely hot surfaces. However, as the temperature ranges of hydraulic fluids are increased, the carbon residue and the tendency of the hydraulic fluid to coke or form sludges becomes important to system design. Two general methods of determining carbon residue are currently used, the Conradson and the Ramsbottom.

Test Methods: Conradson-Federal Test Method 5001.9 (Ref. 115)
ASTM D-189-65 (Ref. 116)
Ramsbottom-Federal Test Method 5002.6 (Ref. 117)
ASTM D-524-64 (Ref. 118)

These methods describe procedures for the determination of the carbon residue left after evaporation and pyrolysis of an oil. They are generally applicable to relatively nonvolatile petroleum products which partially decompose on distillation at atmospheric pressure. Petroleum products containing ash-forming constituents, such as detergents, will have an erroneously high carbon residue depending upon the amount of ash formed.

(1) *Conradson Test:*

In the Conradson test, a weighed quantity of the sample fluid is placed in a crucible and subjected to destructive distillation. The residue undergoes cracking and coking reactions during a fixed period of severe heating. At the end of the heating period, the crucible with the residue is cooled in a desiccator and weighed. The residue remaining is calculated as a percentage of the original sample and reported as the Conradson carbon residue.

(2) *Ramsbottom Test:*

In the Ramsbottom test, a sample of the liquid is placed in a glass coking bulb having a capillary opening. The bulb with the specimen is placed in a metal furnace at approximately 1,020°F. The sample is quickly heated to the point at which all volatile matter is evaporated out of the bulb with or without decomposition while the heavier residue remaining in the bulb undergoes cracking and coking reactions. After a specified heating period, the bulb is removed from the bath, cooled in a desiccator, and weighed. The residue remaining is calculated as a percentage of the original sample and reported as the Ramsbottom carbon residue.

3-4.6.2 Oxidation Stability Tests

A large number of oxidation tests have been proposed. All these tests involve exposing the liquid to air or oxygen at elevated temperatures in order to accelerate the rate of oxidation. Since certain metals such as

iron or copper are catalysts for oxidation, many test procedures involve the use of these metals. Two general techniques are used to indicate oxidation stability. The first involves measuring changes in liquid properties caused by the test. The second involves determining the amount of oxygen that has been removed from the air or the system. Relating the oxygen consumed to time will give the rate of oxidation. A few of the more widely accepted procedures are discussed here.

3-4.6.2.1 Oxidation-corrosion Test

Test Method: Federal Test Method No. 5308.5 (Ref. 119)

Probably the most widely used test for oxidation stability is the oxidation-corrosion test. This test method is used for testing hydraulic fluids and other highly-refined oils to determine their ability to resist oxidation and their tendency to corrode various metals. The test is also used as an accelerated long term storage test.

Five different metal strips—one each of copper, steel, aluminum alloy, magnesium alloy, and cadmium plated steel—are carefully cleaned, polished, and weighed. These metal strips are assembled in a pattern, tied together, and the assembly immersed in a sample of the oil. The oil is held at 250°F for 168 hr while air is bubbled through it. The strips are then removed, cleaned and weighed, and the results are recorded as changes in weight per unit area of surface. Each strip is examined for any evidence of pitting, etching, or stains. In addition, the oil sample is examined before and after the test, and percent changes of neutralization number and viscosity are determined. Several variations of the test are used with different metal specimens and/or test temperatures and/or test times. For example, MIL-L-7808E specifies metal strips of steel, silver, aluminum, and magnesium alloys under conditions of 347°F for 72 hr. MIL-H-8446B specifies a 72-hr test at 400°F with metal strips of silver, copper, steel, and aluminum alloy.

3-4.6.2.2 Steam Turbine Oxidation Test

Test Method: ASTM D-943-54 (Ref. 120)

This test was developed to measure the effectiveness of antioxidant additives and to predict lubricant life. The procedure is actually a combination oxidation and hydrolytic stability test. Given amounts of the test liquid and water are placed in a large test tube, and a coil

of iron wire and copper wire wound together in intimate contact is completely immersed in the test mixture. The test tube is placed in a bath at 95°C and air at 3 liters per hour is bubbled through the test liquid/-water mixture. The test liquid is sampled periodically to determine changes in acidity. A rapidly increasing acidity is taken as the end point of the test. The formation of sludge deposits on the metal coil can also be used to rate liquid stability. This procedure has been found to be particularly useful in determining the effectiveness of inhibitors in petroleum products used as steam turbine lubricants. Since many of these same materials are used as hydraulic fluids, the results of the steam turbine oxidation test are often considered in the selection of petroleum-type hydraulic fluids.

3-4.6.2.3 *Evaporation Tests*

Evaporation loss tests described in par. 3-2.8.2 provide a measure of oxidation stability. These tests are primarily designed to measure the liquid volatility. However, if the temperature at which the test is carried out is high enough that oxidation occurs, the total weight loss experienced by the sample will be a measure of oxidation stability-volatility of the liquid.

3-4.6.2.4 *Thin Film Oxidation Tests*

A frequent occurrence in the operation of hydraulic systems is the exposure to the atmosphere of a large area of metal surface covered by a thin film of hydraulic fluid. One such case is the extension of an actuator rod. Normal oxidation tests involve the use of relatively small surface-to-liquid ratios. A test for determining oxidation properties at large surface-to-liquid ratios has been developed by the Pennsylvania State University Petroleum Refining Laboratory (Ref. 4). The procedure involves passing air and oxygen through a tube containing a large amount of metal chain and a small amount of liquid. Changes in liquid properties occurring after a specific test period are measured.

3-4.6.2.5 *Dornite Oxidation Test*

The Dornite oxidation test is one of the more common absorption-type oxidation tests for hydraulic fluids. Oxygen is circulated through the liquid which is maintained under specified conditions. The total amount of oxygen absorbed is replaced to maintain the

ratio of oxygen-to-liquid. The amount of oxygen that must be added to the system to maintain a desired pressure is a measure of that absorbed by the liquid. Test data are usually accumulated in terms of amount of oxygen absorbed per unit time. Several variations of this test have been developed. Details on them can be found in Ref. 4.

3-4.6.3 **Thermal Stability Tests**

3-4.6.3.1 *Penn State Bomb Test*

The Penn State Bomb Test described in MIL-H-27601 is a widely used thermal stability test. A 20 ml sample of the liquid is placed in a stainless steel pressure cylinder with a 46 ml capacity. Catalysts of 0.5 in. diameter ball bearings of M-10 tool steel, 52100 steel, and naval bronze are also placed in the cylinder. The system is purged with nitrogen, sealed at atmospheric pressure, and the test begun. A temperature of 700°F (371°C) and a nitrogen pressure of 20 psig is maintained for 6 hr. Changes in viscosity, weight of the catalyst ball bearings, and acid or base number are reported as a measure of thermal stability of the liquid.

3-4.6.3.2 *High-temperature Test*

Test Methods: Federal Test Method 2508 (Ref. 121)
ASTM D-2160-66 (Ref. 122)

This method describes a procedure for determining the thermal stability of liquids. The volatile decomposition products are held in continuous contact with the liquid during the test. The method does not measure the temperature at which oil fragments begin to form, but will indicate bulk fragmentation occurring at a specified temperature and testing period.

A sample of the liquid is placed in a glass test cell, and the test cell and contents are degassed to reduce oxidation and hydrolysis. The cell is then sealed under a vacuum and held at 500°F \pm 2°F for a period of 24 hr. The sample is observed during the test for evidence of insolubles, separation, or other changes. The test report includes (1) test temperature and duration, (2) visual appearance of the liquid and test cell, and (3) changes in neutralization number and viscosity of the liquid sample.

3-4.6.3.3 *Sustained High-temperature Stability Tests*

There are no standardized test procedures for sustained high-temperature stability as such. However,

when a hydraulic fluid is being considered for use for long periods in a system operating near its upper temperature limit, normal thermal stability data may not be sufficient to indicate probable performance. In such instances, it is common to test the liquid in a pump loop operating in a high-temperature environment. The pump loop test procedures discussed in pars. 3-2.5.3 (Shear Tests) or 3-3.8.2.1 and 3-3.8.2.2 (Lubrication Tests) are adaptable to high temperature tests. The procedure is to enclose the loop in an oven, and operate the test continuously at the desired temperature for 100 to 1,000 hr.

3-4.6.3.4 Low-temperature Stability Test

Although the term "thermal stability" usually implies high-temperature stability, problems can occur with hydraulic fluid stability at low temperatures. Refer to par. 3-2.14 for a discussion of low-temperature stability and the various applicable tests.

3-4.6.4 Hydrolytic Stability Tests

Hydrolytic stability is determined by exposing the hydraulic fluid to water and measuring the changes that occur, under various environmental conditions, in selected properties of the liquid. A problem that often occurs in these tests is maintaining a sufficient contact area between water and liquid to obtain a measurable reaction. Several of the more common tests are described.

3-4.6.4.1 Beverage Bottle Test

Test Methods: Federal Test Method 3457 (Ref. 123)
ASTM D-2619-67 (Ref. 124)

This method is used for determining the resistance of finished fluids to reaction when in contact with water. It consists of placing 75 g of fluid and 25 g of distilled water in a 7-oz beverage bottle. A cleaned and weighed copper strip is placed in the bottle and immersed in the fluid. The bottle is sealed and placed in a rotating mechanism that turns the bottle end over end at 5 rpm for 48 hr in an oven at 200°F. The container is then removed from the oven, allowed to cool, and examined. Any insolubles formed are removed by centrifuging. The oil and water layers are separated and examined for changes in neutralization number, viscosity, and color. The weight change of the copper strip is also reported, and the physical condition of the strip is observed.

3-4.6.4.2 Other Hydrolytic Stability Tests

To determine the hydrolytic stability of fluids whose rate of hydrolysis is low, or to predict hydrolytic stability in closed systems at high temperatures, a metal bomb must be used in place of the beverage bottle. Test procedures are quite similar to those used for the beverage bottle test except that no metal strip is added. Shaking assemblies, such as those available from the American Instrument Company, are well suited for this test. These particular assemblies oscillate a high-temperature high-pressure reaction vessel $\pm 15^\circ$ at 36 cycles per min. Reflux tests present another general technique. While procedures have not been standardized, the essential features are that measured amounts of water and fluid are placed in a container and heated to the temperature at which the oil boils. The vapors are condensed, and refluxing is continued for a specified period of time. Changes in the fluid are determined, and the development of any acidity in the water layer is measured. These data are used as an indication of hydrolytic stability. Simple storage tests are also a measure of hydrolytic stability. Measured quantities of fluid and water are placed in a bottle or other container, agitated, and stored at desired temperatures for a desired period of time. The samples are examined periodically to determine changes in appearance and, at the end of the test, are examined for the formation of insolubles, gels, or other physical and chemical changes. Various types of metals, elastomers, surface coatings, etc., can be added to the test containers to determine their effect.

3-4.6.5 Radiation Resistance Tests

The usual test methods for determining radiation resistance by hydraulic fluids are based upon radiation exposure followed by determination of changes in the liquid. Certain selected properties—such as viscosity and neutralization number, etc.—of the fluid are measured before the test. The fluid is subjected to a given amount of radiation exposure and the properties are measured after exposure. Changes can vary from complete destruction of the fluids and loss of structural integrity to minor variations in various properties. This is a static test method and gives considerable information on performance of fluids exposed to radiation.

Under development, however, are various dynamic test procedures. These procedures are based upon the actual operation, in the presence of radiation, of some test devices such as a simulated hydraulic pump test loop containing the test liquid. Also being studied is the

effect of various types of radiation on the test liquid. For example, gamma radiation is known to have a more destructive effect than alpha or beta radiation. Testing for radiation effects becomes complicated and expensive. Equipment needed is extensive and costly. Results vary greatly from test to test and also from sample to sample. Considerable effort is being expended by the military on studies of potentially useful hydraulic fluids and their radiation resistance.

3-5 CORROSIVENESS

In its broadest meaning, corrosion refers to the deterioration of a metallic surface by chemical or electrochemical action; a familiar example is the rusting of iron. The corrosiveness of a hydraulic fluid relates to its tendency to promote or encourage corrosion in a hydraulic system. It is obviously desirable to maintain the corrosiveness of a hydraulic fluid at as low a level as possible.

The corrosiveness of a hydraulic fluid, usually at its lowest value when the fluid is new and unused, can be affected by a number of variables such as temperature, load, moisture, chemical nature of the liquid, oxidation stability, the type and amount of degradation products formed, the dispersion of the products in the system, and numerous other variables. Only a few of these variables, however, are parameters of the liquid. Variables such as temperature, load, and exposure to moisture, etc., are system mechanical factors and can—through proper system design and the use of the correct hydraulic fluid—be controlled within a range of acceptable limits. Fluid parameters—those variables that relate to the corrosiveness of the liquid such as chemical nature and oxidation stability—are fundamental properties of the liquid and cannot be varied except by the use of additives (see Chapter 5).

3-5.1 CHEMICAL CORROSION

Purely chemical corrosion is probably the most prevalent type of corrosion found to exist in fluid power systems. Although starting rapidly, it may often become low as soon as a layer of corrosion products has been formed on the metallic surface. If, however, the layer or corrosion products are being continually cracked or removed, corrosion will continue at its original rate. Of the various types of corrosion, the two that occur in most systems are oxidation and acidic corrosion. Oxidation is limited to the surface of metals and

its results are exhibited by an accumulation of metal oxides. Acidic corrosion refers to the deterioration of the metallic surface caused by the metal actually being dissolved by acids and washed away, leaving a pitted surface.

Rusting is the oxidation of the base iron in the metal structures. The oxidation is usually catalyzed or increased by the presence of dissolved air and water in the system liquid. Prevention of oxidation is theoretically the easiest corrosion action to control. Simple exclusion of air and moisture from the system could eliminate rusting. However, because it is almost impossible to completely exclude all air and moisture from a hydraulic system, numerous additives are used as oxidation and corrosion inhibitors (see Chapter 5).

Oxidation of the hydraulic fluids while in use produces acid-type products which can rapidly increase the corrosiveness of the fluid. It is, therefore, desirable to maintain a high level of oxidation stability in the fluid. There are numerous inhibitors which can reduce the acid corrosion tendencies of a hydraulic fluid. A discussion of the various corrosion inhibitors and their mode of action is presented in Chapter 5.

The corrosive tendencies of a liquid are frequently increased by the presence of various metals which act as catalysts. Copper is a common example. Many liquids become much more corrosive than usual in the presence of copper; thus several of the test procedures for determining corrosion properties of liquids make use of a copper catalyst. The problem is basically one of liquid-metal compatibility and is discussed in par. 3-6.1.

3-5.2 ELECTROCHEMICAL CORROSION

While almost any chemical reaction can be called electrochemical, the term is usually limited to cases with spatially separated anodic and cathodic areas, so that corrosion is accomplished by electric current flowing for a perceptible distance through the metal. It is not necessary to have two metals for electrochemical corrosion. All that is needed is the metal, a material of a different electric potential and a conductance path between them. A corrosion product or liquid can serve as the source of the second electric potential (Ref. 125).

Galvanic corrosion is probably the most common form of electrochemical corrosion. Galvanic corrosion occurs when dissimilar metals, in electrical contact with each other, are exposed to an electrolyte. A current, called a galvanic current, then flows from one metal to the other. Galvanic corrosion is that part of the resulting corrosion of the anodic (positive) member of the metal couple.

Many hydraulic fluids are not good electrolytes when new and do not promote galvanic or electrochemical corrosion. However, contaminants that enter or form in the fluid during use, and some types of additives, may give the liquid electrolytic properties. Several precautions can be taken to stop or reduce the electrochemical action of the galvanic couple and reduce the corrosion; e.g., using similar metals, insulating the metals, or eliminating the electrolyte. These steps are frequently impractical and other precautions, such as using corrosion inhibitors, must be taken.

3-5.3 CORROSIVENESS TESTS

Numerous test methods have been proposed and developed for determining the corrosive properties of liquids. While most of the tests are universal in that they are designed for any type of liquid or lubricant, certain tests have been developed specifically for gear lubricants, for hydraulic fluids, or for other special liquids. These corrosiveness tests fall into three general categories: (1) metal-liquid tests where a metal surface is exposed to the liquid for a given length of time at given conditions, (2) fog or humidity cabinet tests where a strip of metal is coated with the liquid and exposed to extremely humid conditions for a predetermined period of time, and (3) engine tests where the liquid is tested in a gear box of an engine under controlled conditions.

3-5.3.1 Metal-liquid Corrosiveness Tests

A large number of metal-liquid corrosiveness tests have been developed. Most of these tests are similar in that a metal sample is exposed to the liquid under controlled conditions. The metal is then examined for evidence of corrosion and the liquid is examined for changes in properties. These tests can also be considered as liquid-metal compatibility tests. Two of the more common types of tests are described and also noted in Table 3-12 along with other tests of the same type.

(1) *Oxidation-corrosion Test*

Test Method: Federal Test Method 5308.5 (Ref. 119)

This test is probably the most commonly used liquid-metal corrosiveness test. It is described in detail in par. 3-4.6.2.1. In this test, five different metal strips—one each of copper, steel, aluminum alloy, magnesium alloy, and cadmium plated steel—are assembled in a pattern and the assembly is immersed in a sample of the

test liquid and is heated at 250°F for 168 hr while air is bubbled through the liquid. After the test, the strips are examined for evidence of pitting and corrosion, and the liquid sample itself is examined for changes in basic properties. The oxidation-corrosion test, or variations of it, is frequently called for in property specifications of military hydraulic fluids. The acceptable corrosion limits for several military specification hydraulic fluids, as determined by the oxidation-corrosion test (or variations) are given in Table 3-13.

(2) *Copper Corrosion (Copper Strip) Test*

Test Methods: Federal Test Method 5325 (Ref. 126)
ASTM D-130-65 (Ref. 127)

This method describes a procedure for the determination of the corrosiveness to copper of fuels, gasolines, cleaners, fuel oils, and other petroleum products.

A polished copper strip is immersed in a 30-ml sample of the liquid and heated at the temperature (normally 122° or 212°F) and for the time (normally 2 to 3 hr) called for in the liquid specification. At the completion of the test period, the copper strip is removed and compared with a series of copper strip corrosion standards (available from ASTM). The results are reported as the number of the corrosion standard with which the test strip compares. Standards vary from a No. 1a (slight tarnish) to No. 4c (corroded glassy or jet black).

3-5.3.2 Humidity-type Corrosiveness Tests

Several corrosiveness test procedures using a fog or humidity cabinet have been developed. The tests are similar in that a metal specimen is coated with the test liquid and placed in a cabinet with constant high humidity. In some instances the fog is treated with various chemicals to simulate actual conditions, i.e., sodium chloride salt added to simulate sea water. These tests are not basically corrosiveness tests; they are primarily intended to determine the corrosion-protecting qualities of a liquid in the presence of a corrosive environment. Two of the more common test procedures are described and also listed in Table 3-14 along with other tests of the same type.

(1) *Corrosion-fog Cabinet*

Test Method: Federal Test Method 5312 (Ref. 128)

This method is used for determining the rust inhibiting properties of nonaqueous liquids, greases, and preservative compositions. The method consists of coating low-carbon, cold-rolled steel plates with the test liquid, rotating the plates in a fog cabinet under specified con-

TABLE 3-12.
LIQUID-METAL CORROSIVENESS TEST METHODS

Test Method	Title	Procedure
Federal Test Method 5308.5	Corrosiveness and Oxidation Stability	5 Metal strips—copper, steel, aluminum, magnesium, cadmium plated steel,—immersed in test liquid for 168 hr at 250°F; with air agitation.
Federal Test Method 5325 ASTM D-130-65	Copper Strip Corrosion	Polished copper strip immersed in test liquid 2 to 3 hr, 122°F (50°C) or 212°F (100°C).
Federal Test Method 5305	Corrosion at 450°F	Copper and silver strip immersed in test liquid for 50 hr, 450°F.
Federal Test Method 5321	Lead Corrosion	Strips of lead and copper are rotated in test liquid 1 hr, 325°F; air bubbled through liquid.
Federal Test Method 5324	Copper Stain	Polished copper strip immersed in used test liquid 3 hr, 300°F; nitrogen bubbled through liquid.
Federal Test Method 5311	Rust Inhibiting (Static Water Drop)	Drop of water placed on 3 sheet-steel plates immersed in test liquid, one week, 140°F.
Federal Test Method 4011 ASTM D-665-60	Rust Preventing—Steam Turbine Oils	Cylindrical steel specimen immersed in test liquid-water mixture, 24 hr, 140°F (60°C)
Federal Test Method 3457 ASTM D-2619-67	Beverage Bottle Test	Copper strip immersed in water-test liquid mixture, 48 hr, 200°F.

References:

- (1) *Federal Test Method Standard No. 791a*, Test Methods 3457, 5308.5, 5325, 5305, 5321, 5324, 5311, 4011.
- (2) *ASTM Standards 1967*, Designation D-130-65, Part 17, p. 82; Designation D-665-60, Part 17, p. 253; Philadelphia, American Society for Testing Materials, 1967.
- (3) *ASTM Standards 1969*, Designation D-2619-67, Part 17, p. 997; Philadelphia, American Society for Testing Materials, 1969.

ditions of temperature and humidity as called for by the liquid specifications, and observing the plates for the formation of rust. The result is reported as the time required for three 1-mm diameter rust spots to form on the surface of at least two plates or until the specified test period required by the fluid specification is completed, whichever comes first.

(2) *Protection-salt Spray*

Test Method: Federal Test Method 4001 (Ref. 129)

This method is intended for the determination of the corrosion resistance of a fluid in the presence of a salt-type atmosphere. Steel test specimens are coated with the test fluid and suspended in a fog chamber. The fog consists of an atomized spray of a solution of 20 parts,

TABLE 3-13.

OXIDATION-CORROSION LIMITS OF SEVERAL MILITARY HYDRAULIC FLUID SPECIFICATIONS

Military Specification	Test Method or Test Description	Fluid Changes		Metal Changes						
		Viscosity Change, %	Neutralization No. Change	Weight Change, mg/cm ²					Pitting, Etching, Visible Corrosion	Copper Corrosion Allowed
				Copper	Steel	Aluminum	Magnesium	Gold Plated Steel		
<u>Petroleum Hydraulic Fluids</u>										
MIL-H-5606B	Federal No. 5308.5 (168 hr at 250°F)	-5, +20 at 130°F	< 0.20	± 0.6	± 0.2	± 0.2	± 0.2	± 0.2	None at 20X	< ASTM No. 3
MIL-H-6083C	Federal No. 5308.5 (168 hr at 250°F)	-5, +20 at 130°F	< 0.30	± 0.6	± 0.2	± 0.2	± 0.2	± 0.2	None at 20X	Slight Etching
MIL-H-13866B	168 hr at 212°F	-5, +20 at 100°F	< 0.5 (Total)	- 0.2	- 0.2	-	-	-	None at 20X	
MIL-H-27601A	Federal No. 5308.5 (48 hr at 347°F)	-5, +20 at 100°F	< 0.2 (Total)	± 0.6	± 0.2	(± 0.2 for Silver)			-	-
<u>Phosphate Ester</u>										
MIL-H-19457B	168 hr at 130°F	-	-	-	± 0.2	± 0.2	(± 0.2 for Brass and Zinc)		None	-
<u>Silicate Ester</u>										
MIL-H-8446B	Federal No. 5308.5 (72 hr at 400°F)	± 35 at 210°F	< 0.1 (Total)	± 0.4	± 0.2	± 0.2	(± 0.2 - Silver)		None at 20X	Slight Discolor

TABLE 3-14.
FOG OR HUMIDITY CORROSIVENESS TEST METHODS

Test Method	Title	Procedure
Federal Test Method 5312	Corrosion	3 or more steel plates, 2 in. x 4-1/8 in., coated with test liquid, rotated in fog cabinet, 110° to 160°F. Test run until rust occurs on at least two plates, or for a specified time.
Federal Test Method 4001	Salt-Spray	Similar to above, 95°F; solution is 20 percent sodium chloride, 80 percent distilled water.
Federal Test Method 5329 ASTM D-1748-62T	Rust Protection- Humidity Cabinet	Similar to Federal Test Method 5312 above, 120°F.
Federal Test Method 5323	Protection Tests	Similar to Federal Test Method 5312 above.
Federal Test Method 5322	Corrosivity	Brass clip-on sheet disk coated with test liquid, placed in humidity cabinet, 50 percent relative humidity, 80°F, 10 days.

References:

- (1) *Federal Test Method Standard No. 791a*, Test Methods 5312, 4001, 5329, 5323, 5322.
- (2) *ASTM Standards 1967*, Designation D-1748-62T, Part 17, p. 672, Philadelphia, American Society for Testing Materials, 1967.

by weight, sodium chloride and 80 parts distilled water. The temperature in the chamber is kept between 92° and 97°F. The test shall be conducted for as long as required by the liquid specification. Criteria for determining if the candidate liquid passes or fails the test are to be supplied by the liquid specification.

3-5.3.3 Gear-box and Engine Corrosiveness Tests

Several test methods have been developed to evaluate the corrosiveness of lubricating oils used in gear boxes. These tests were not developed for testing hydraulic fluids and are not often used in their evaluation. However, they are mentioned here as they are a means of evaluating liquids under conditions of high torque and high loads. Three of the more common tests are described in Table 3-15.

3-6 COMPATIBILITY

A hydraulic fluid must be compatible with the materials used in the hydraulic system, including metals, plastics, surface coatings, elastomers, and occasionally other materials of construction, lubricants, and other hydraulic fluids. If the hydraulic fluid in any way attacks, destroys, dissolves, or changes any part of the hydraulic system; the system may become inoperable and, conversely, any changes in the hydraulic fluid caused by interaction with the system materials can also cause system malfunction. Therefore, compatibility of a hydraulic fluid with the system means that the fluid should not attack the system, and the system should not attack the fluid.

Compatibility must be considered from several points of view. First, there should be compatibility of the hydraulic fluid with the hydraulic system. Of primary concern is compatibility with the metals of

TABLE 3-15.
GEAR-BOX CORROSIVENESS TEST METHODS

Test Method	Title	Procedure
Federal Test Method 5317	Load-carrying, Wear, Stability, and Corrosion Characteristics	The test unit is a 3/4-ton Army truck hypoid rear-axle carrier, 5:83 to 1 ratio. The test fluid is used as the lubricant, temperature maintained at 200°-250°F, load of 32,311 in.-lb at 62 rpm. Test is run for 30 hr.
Federal Test Method 5318	Moisture Corrosion Characteristics - Universal	Test unit is Chevrolet passenger car rear axle. 25 ml of distilled water is added to the test fluid, temperature of 180°F; 2,400 rpm for 4 hr test. Unit is then stored for 10 days, opened and examined for corrosion.
Federal Test Method 5326	Moisture Corrosion Characteristics-Gear Lubricants	Test unit is a Spicer differential assembly. One ounce of distilled water is added to test fluid temperature of 180°F; 2,500 rpm for 4 hr. Unit is then stored as required by fluid specification, opened and examined for corrosion.

References: (1) *Federal Test Method Standard No. 791a*, Test Methods 5317, 5318, 5326.

construction and the elastomers used for sealing. Also important are the various surface treatments of materials in or near the system, such as paints and special surface finishes. Second, there should be compatibility of the hydraulic fluid with the system environment. Breakage, leakage, and spillage all too frequently bring the hydraulic fluid into contact with its immediate environment. Of concern here are paints, fabric or plastic linings or covers, insulation and electrical wiring, and structural materials used near the hydraulic system. Third, there should be compatibility of the hydraulic fluid with other liquids and lubricants it may contact. Of concern here is additive susceptibility, use of substitute hydraulic fluids, and choices of lubricants for the system. Each of these factors must be examined individually and in combination for compatibility with the hydraulic fluid.

There is often difficulty in determining the compatibility of a hydraulic fluid with the hydraulic system. Because of the wide range of operating conditions and the large number of possible materials, there have been very few Federal or ASTM test procedures developed for determining compatibility. When a question of compatibility arises, the normal test procedure is to expose the material in question to the hydraulic fluid (under simulated service conditions, if possible) and determine changes in the material. One unique facet of this type of procedure is that emphasis is placed on the material and not on the hydraulic fluid. The question then arises whether compatibility is a property of the

hydraulic fluid or of the material. Because compatibility is an interaction between a hydraulic fluid and enumerable other materials, hydraulic fluid specifications usually include a limited number of requirements on compatibility. The most frequently encountered examples are rubber swelling requirements. Also, most hydraulic fluid specifications require that all liquids qualified under the specification be compatible with each other.

3-6.1 HYDRAULIC FLUID COMPATIBILITY WITH METALS

Compatibility of a hydraulic fluid with the metals used in a hydraulic system is most important. Care must be taken that system design excludes all metals that are damaged by the liquid or that degrade the liquid. Liquid-metal compatibility, in its strictest sense, includes only chemical interrelationships; however, the topic is broadened here to include any influence the hydraulic fluid may have on metal fatigue and cavitation.

It is common practice to use copper, silver, bronze, aluminum, steel, magnesium, and many other metals as structural materials in hydraulic systems. Most petroleum-base hydraulic fluids are not normally affected by these materials although some metals, especially copper, act as catalysts after degradation starts in some petroleum liquids. However, many of the newer

synthetic fluids may not be compatible with one or more of the conventional metals. For example, diester fluids such as the turbine engine oil MIL-L-7808 are affected by copper and its alloys above 200°F. At 500°F, which is 200°F above its maximum usable temperature, such a diester still has a life of 8 to 12 hr in a sealed system. If a small piece of brass or copper is present, the fluid is reduced to a thick, black, molasses-like substance of high acidity and foul odor within an hour (Ref. 62).

Liquid-metal compatibility may be measured by a number of tests. These techniques usually involve exposing the metal to the liquid under a variety of conditions and determining any changes in the liquid or the metals. Many of the tests mentioned in the paragraphs on Chemical Stability (par. 3-4.1) or Corrosiveness (par. 3-5) are quite useful and have been widely used.

Difficulty often arises in attempting to relate test conditions to actual service conditions. Many conditions that occur in service cannot be anticipated and incorporated into the test. One example is galvanic corrosion. Hydraulic fluids may become electrolytes between dissimilar metals during use and cause considerable corrosion. It then becomes necessary to study metal-to-metal couples in the presence of candidate hydraulic fluids. Most fluid manufacturers have conducted extensive research into the liquid-metal compatibility of their products and data are available to prospective purchasers. In most cases, hydraulic fluids are compatible with all common metals used in construction of hydraulic systems, and the fluid manufacturers only provide data for those instances where the fluid and metal are not compatible.

3-6.1.1 Metal Fatigue

Metals fail through fatigue when they are subjected to excessive local stresses, either cyclic or unidirectional. In both cases, the fatigue life of a metal can be affected by its environment. If the environment is corrosive, resistance to fatigue is reduced (Ref. 125). The resultant damage from the combination of corrosion and stress will be worse than the damage produced by either individually. Two basic types of combinations of stress and corrosion are recognized—stress corrosion where the stress is static and tensile, and fatigue corrosion where the stress is cyclic.

The mode of failure in both instances is similar. As a result of fatigue, corrosion, or a combination of the two, small pits or cracks are produced in the metal. The corrosion then acts on the bottom of the cracks or pits in such a way as to produce a greater stress concentration than would be produced by stress alone. Failure

occurs from the progression of the cracks across a section of the metal.

For each metal, the degree to which it is affected by stress corrosion is associated with its environment. The hydraulic fluid constitutes the environment “seen” by the metals in the hydraulic system. If the hydraulic fluid is corrosive to the metals, the fatigue resistance of the metals will be reduced. However, the environment frequently will not be as corrosive to the metal if the stresses are absent.

The effect of the hydraulic fluid on the fatigue life of a metal is not a problem that occurs very often. The degree of corrosiveness required to produce a significant reduction in fatigue life is usually much greater than normally occurs in hydraulic systems. For this reason, almost no work has been done in this area. Because of the protective nature of many hydraulic fluids and the use of corrosion inhibitors, the corrosion level of most hydraulic fluids tends to be low. If excess corrosiveness is present, it is usually an indication that the limits of the hydraulic fluid are being exceeded, or that excess contamination is present. In such cases, the presence of the corrosiveness itself is dangerous and can produce system malfunction.

3-6.1.2 Cavitation

Cavitation has been defined as the “process of formation of the vapor phase of a liquid when it is subjected to reduced pressure at constant ambient temperatures” (Ref. 130). Cavitation damage occurs when the resultant vapor cavities in the fluid collapse near a metal surface on exposure to high pressure. The exact mechanism by which damage occurs is not known, but most authors suggest a form of mechanical erosion or corrosion.

Cavitation damage is often more severe if the cavities consist of a vacuum or of the vapor of the liquid than if they contain some foreign gas, such as air. With the trend toward the use of pure fluids with high pressure differentials and high frequency vibration, cavitation becomes an increasingly important problem.

Erosion or “wearing away” of the metal surface by action of the liquid producing a “pelted” surface seems to be the most prominent theory for cavitation damage. The erosion is caused by the liquid leaving the metal surface and creating a vacuum into which air and liquid vapors are released from the liquid to form a bubble. The bubble is maintained until an area of high pressure is encountered and the bubble collapses suddenly, producing a “hammering” effect. When this action is repeated in rapid succession, the metal is worn away.

Other mechanical effects such as noisy operation and vibration are produced due to the repeated "hammering" effect of the collapsing bubbles (Ref. 131).

Cavitation damage can occur in almost any component in a hydraulic system. However, the damage usually occurs where the high pressure-low pressure-high pressure sequence required occurs often, rapidly, and with high pressure differentials. The components most subject to damage are the hydraulic pump, venturis, and valves.

Cavitation in pumps occurs when the liquid cannot enter the pump fast enough to fill the volume or when the liquid cannot keep up with moving pump elements. Cavitation in venturis occurs when the high fluid velocity in the throat drops the pressure below the vapor pressure of the liquid. Cavitation in valves occurs

in a manner similar to that in venturis. Once cavitation is established in a pump, valve, or venturi, the flow rate remains constant unless some physical change is made—such as increasing the throat opening in a venturi.

There are numerous variables that effect cavitation damage. Some variables are mechanical factors of the system design and some are properties of the fluid. Mechanical factors include suction pressure, venting, liquid velocity, film thickness, temperature, and surface roughness. Liquid properties that effect cavitation are vapor pressure, viscosity, density, bulk modulus, surface tension, and additives. The effect of these variables on cavitation is given in Table 3-16.

A distinction must be made between the amount of cavitation and the extent of cavitation damage. Frequently, a reduction in the amount of cavitation will

TABLE 3-16.
EFFECT OF MECHANICAL AND LIQUID VARIABLES ON CAVITATION¹³⁰

Variable	Cavitation	Comment
<i>Mechanical Factors:</i>		
Increasing Suction Pressure	Reduced	Increased pressure maintains a positive pressure throughout pump; reduces probability of low pressure cavity formation in pump.
Venting	Reduced	Venting reduces cavitation if it de-aerates the system and removes high vapor pressure dissolved gases.
Increasing Liquid Velocity	Increased	
Reducing Lubricant Film Thickness	Increased	Cavitation is increased probably because the film is in compression and pressure differences are large.
Increased Temperature	Increased	Cavitation and cavitation damage are probably increased due to higher vapor pressure.
Increased Surface Roughness	Increased	Cavitation increases, probably because of the creation of more high-low-high pressure sites.
<i>Liquid Factors:</i>		
Lower Vapor Pressure	Reduced	
Higher Viscosity	Reduced	
Higher Density	Increased	
High Bulk Modulus	Increased	
Increased Surface Tension	Reduced	

result in an increase in cavitation damage. This is because many of the variables that tend to reduce the amount of cavitation by reducing the formation and growth of cavities, also increase the collapse rate, and, therefore, the rate of energy released when the cavities collapse. This action has the effect of concentrating the energy into a smaller area and producing more severe damage. One example of this "double-acting" effect of inhibiting cavitation occurs when the vapor pressure is reduced. Lower vapor pressure tends to inhibit the formation of cavities but results in a lower pressure inside the cavities that do form, thereby increasing the rate of collapse and the amount of damage.

Cavitation mainly occurs in two general situations—thin films of lubricants, and full streams of liquid. In both cases, the high-low-high-pressure sequence is found. One instance of cavitation in a thin film is shown in Fig. 3-55. High pressure occurs on the gear teeth surfaces as the lubricant approaches the pitch point and is compressed. The low pressure, cavity formation, and cavity collapse occur as the lubricant passes the pitch point. Cavitation occurs in the free stream whenever an orifice or venturi is encountered that produces the high-low-high pressure sequence as shown in Fig. 3-56. The venturi effect can occur in valves, orifices, fittings, and other components of a hydraulic system.

3-6.2 ELASTOMERS

Almost all seals and packings used in a hydraulic system are made from synthetic or natural rubbers which have an elastomer as the main ingredient. An elastomer is a material exhibiting little plastic flow, and quick and nearly complete recovery from an extending force (Ref. 132). Such materials are usually modified by

additives and treatments to make a finished elastic compound. While the number of basic elastomers is small, the variety of finished compounds that can be made is almost infinite. It is usually possible to develop a compound that is compatible with hydraulic fluids under any normal environmental conditions.

The hydraulic fluid usually has more effect on the seal or packing compound than the compound has on the hydraulic fluid. In most instances, the compound is almost inert as far as any harmful effects on the liquid are concerned. However, some liquids attack and destroy some seal materials. The usual method of determining if a liquid and an elastomer are compatible is to measure selected properties of the elastomer before and after immersion in the liquid. The common properties used to compare or evaluate various elastomers are described in Table 3-17. Other properties (not listed in Table 3-17) of importance are corrosive effects on metals, thermal resistance, permeability, coefficient of thermal expansion, and coefficient of friction.

The greatest difficulty in evaluating liquid-elastomer compatibility is the selection of test conditions. Seals are subjected to a wide variety of operating parameters including variables such as temperature, pressure, load, speed, abrasion, and stop-start conditions. In addition, changes in the chemistry of the liquid occur during use by oxidation, thermal processes, corrosion, and contamination; there are also different requirements for static or dynamic seals. Evaluation of dynamic seals must take into account the complete range of conditions expected in service because a change in the conditions within the expected range may have an effect on the compatibility. In general, the final determination of liquid-elastomer compatibility must be made in the intended system (or a simulated system) over the anticipated range of operating conditions.

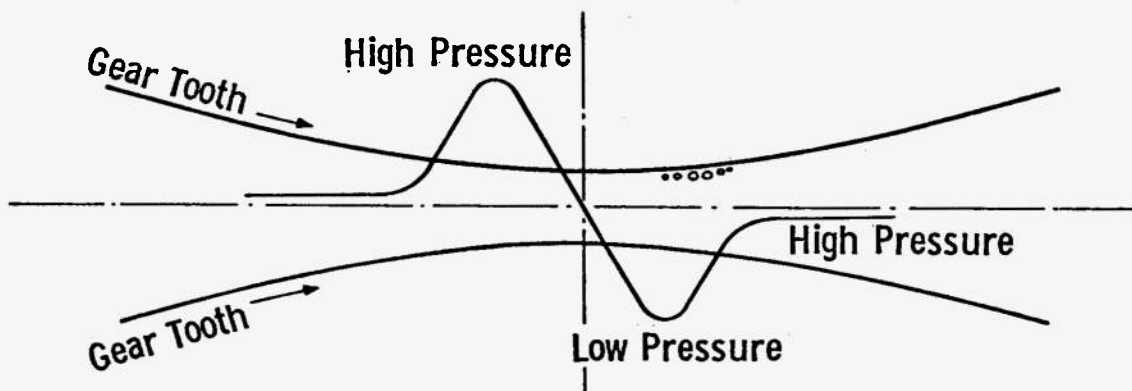


Fig. 3-55. Cavity Formation and Collapse Between Rollers or Gear Teeth¹³⁰

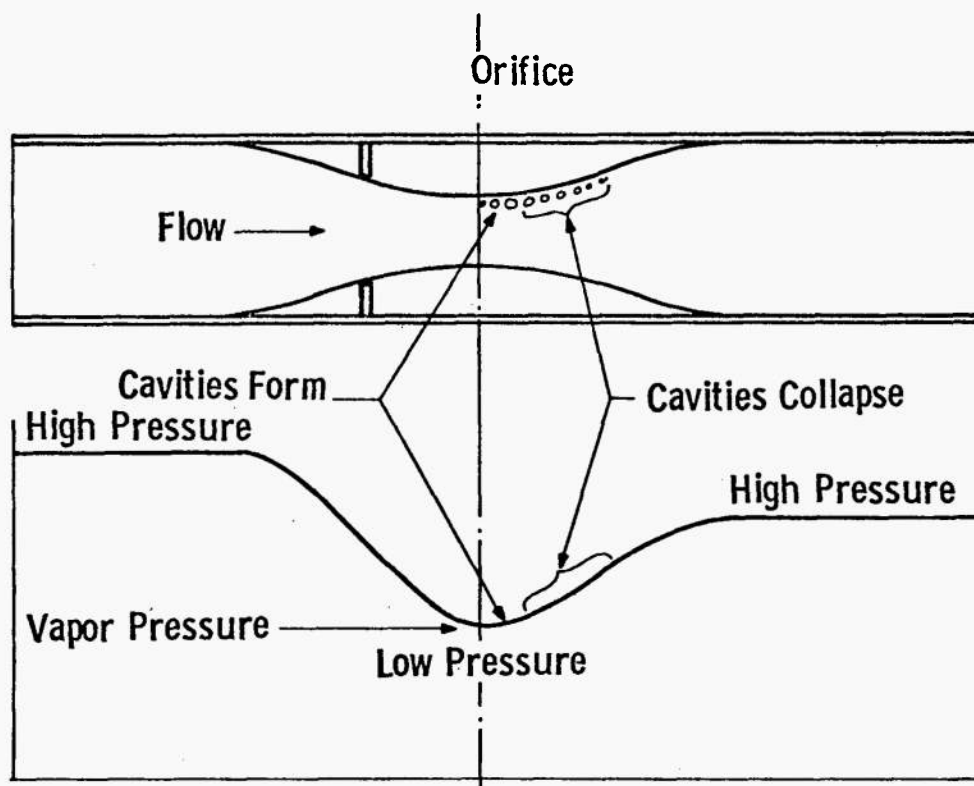
Fig. 3-56 .Cavity Formation and Collapse in an Orifice¹³⁰

TABLE 3-17.
PROPERTIES OF ELASTOMERS

Property	Definition
Hardness	Hardness measured on the Shore A durometer scale, calibrated to a durometer reading of 100 on flat glass.
Tensile Strength	The force in psi required to rupture a standard specimen.
Ultimate elongation	The increase in length, expressed as a percent of original length, a standard specimen will undergo before breaking.
Modulus	The stress at a predetermined elongation, usually 100 percent.
Volume change	The change in volume, expressed as a percent of original volume, of an elastomer after contact with a media (hydraulic fluid).
Compression set	The percent of original deflection by which an elastomer fails to recover in air after a fixed time under specified load and temperature.

3-6.2.1 Basic Elastomer Materials

Several elastomer materials have been developed for use as seals and packings. A brief description of the 15 most commonly used basic types of elastomers is given in the paragraphs which follow (Ref. 132). Some common trade names and recommended uses are given in Table 3-18. A comparative rating of various properties is given in Table 3-19. Table 3-20 lists data on the compatibility ratings of several commercial hydraulic fluids with the elastomers described.

(1) *Nitrile or Buna N (NBR)*

Temperature Range: -65° to 250°F (-54° to 121°C)

This elastomer is a copolymer of butadiene and acrylonitrile. As the nitrile component increases, resistance to petroleum base liquids increases, but low temperature flexibility decreases. Nitrile is the most widely used elastomer today. Nitrile compounds are superior to most elastomers with regard to compression set or cold flow, tear, and abrasion resistance.

(2) *Buna S Rubber (SBR or GRS)*

Temperature Range: -65° to 225°F (-54° to 107°C)

SBR rubber is best known under its former designation of Buna S or GRS, which refers to the U. S. Government rubber made during World War II. SBR and natural rubber account for almost 90 percent of world rubber consumption. These two materials are not generally used in seals (except for those in automotive brake systems).

(3) *Butadiene Rubber (BR)*

Butadiene (polybutadiene) has properties similar to natural rubber. It is not quite as good as natural rubber, but in some cases exhibits improved low temperature characteristics.

(4) *Butyl Rubber (IIR)*

Temperature Range: -65° to 225°F (-54° to 107°C)

Butyl rubber is an all petroleum product made by co-polymerizing isobutylene and isoprene. Brominated and chlorinated butyl rubbers are also available. Inner tubes and the inside layer of tubeless tires account for most of the butyl rubber consumption. Butyl has excellent resistance to permeation and is used in vacuum applications.

(5) *Chloroprene Rubber (CR)*

Temperature Range: -65° to 300°F (-54° to 149°C)

Chloroprene rubbers (known as neoprene) are homopolymers of chloroprene (chlorobutadiene). They were an early synthetic rubber. Chloroprene tends to crystallize in a stressed condition at low temperatures.

(6) *Chlorosulfonated Polyethylene (CSM)*

Temperature Range: -65° to 250°F (-54° to 121°C)

CSM rubber has good acid resistance but its mechanical properties, compression, and permanent-set

characteristics are less than desired for seal applications.

(7) *Ethylene Propylene Rubber (EPM)*

Temperature Range: -65° to 300°F (-54° to 149°C)

Although EPM rubber was introduced only recently, its use has become widespread because of its excellent resistance to the widely used phosphate ester-type hydraulic fluids.

(8) *Fluorocarbon Rubber (FPM)*

Temperature Range: -20° to 400°F (-29° to 204°C)

Fluorocarbon rubbers were first introduced in the mid-1950's and have grown to major importance. They will withstand temperatures as high as 600°F (316°C) for short periods and as low as -65°F (-54°C) in some static uses. They exhibit maximum resistance to deterioration by test and functional fluids.

(9) *Isoprene Rubber-Synthetic (IR)*

Isoprene rubber (polyisoprene) is a synthetic elastomer with the same chemical composition as natural rubber.

(10) *Natural Rubber-Natural Polyisoprene (NR)*

Natural rubber is not used to a great extent for seals and packings. Petroleum liquids seriously attack natural rubber compounds. Like neoprene, natural rubber tends to crystallize in the stressed condition.

(11) *Polyacrylic Rubber (ACM)*

Temperature Range: 0° to 350°F (-18° to 177°C)

ACM rubber has outstanding resistance to petroleum fuels and oils. There are numerous types of the ACM rubber available and all are polymerization products of acrylic acid esters. The greatest usage of ACM rubber is in automatic transmission and power steering gear seals.

(12) *Polysulfide Rubber*

Temperature Range: -65° to 225°F (-54° to 107°C)

Polysulfide rubber was one of the first synthetic polymers; it is prepared from dichlorides and sodium polysulfides. It has unique combinations of solvent resistance, low temperature flexibility, and oxygen and ozone resistance. It has poor heat resistance, mechanical strength, and compression set.

(13) *Polyurethane Rubber*

Polyurethanes have superior mechanical and physical properties. However, they cannot withstand water, acids, ketones, and chlorinated or nitro hydrocarbons. They have poor compression set and tend to soften excessively above 250°F (121°C). Because of the many polyurethane rubber compounds, with minimum temperature at which each may be used varying from compound to compound, no lower temperature restriction can be stated.

TABLE 3-18.

COMMON TRADE NAMES AND RECOMMEND USES OF BASIC TYPES OF ELASTOMERS

Elastomer	Trade Names and Manufacturers		Recommended Uses
Nitrile or Buna N (IIR)	Chemigum Butaprene Parsacril Hycar Hercrol Polysar Krynac	Goodyear Tire & Rubber Co. Firestone Tire & Rubber Co. Naugatuck Chemical Goodrich Chemical Co. Heresite & Chemical Co. Polymer Corp., Limited	General purpose sealing Petroleum oils and fluids Water Silicone greases and oils Di-ester base lubricants (MIL-L-7808) Ethylene glycol base fluids (Hydrolubes)
Buna S (SBR or GRS)	(Too numerous)		Automotive brake fluid Alcohols (low molecular weight) Water
Butadiene (BR)	Ameripol CB Budene Cisdene Diene	Goodrich-Gulf Chemicals, Inc. Goodyear Tire & Rubber Co. American Synthetic Rubber Corp. Firestone Synthetic Rubber Corp.	
Butyl (IIR)	Enjay Butyl Hycar 2202 Polysar Butyl	Enjay Chemical Co. F. F. Goodrich Chemical Co. Polymer Corp., Limited	Phosphate ester type hydraulic fluids (Skydrol, FRYQUEL(Cellulube), Pydraul) Ketones (MEK, Acetone) Silicone fluids and greases
Chloroprene (CR)	Neoprene	E. I. duPont de Nemours Co.	Refrigerants (Freons, NH ₃) High aniline point petroleum oils Mild acid resistance Silicate ester lubricants
Chlorosulfonated Polyethylene (CSM)	Hypalon	E. I. duPont de Nemours Co.	
Ethylene	Nordel	E. I. duPont de Nemours Co.	Phosphate ester base hydraulic fluids (Skydrol, FRYQUEL(Cellulube), Pydraul)
Propylene	Royalene Enjay EPR Dutral N Olethene	Naugatuck Chemical Enjay Chemical Co. Montecatini Soc. Gen. Avisun Corp.	Steam (to 400°F) (204°C) Water Silicone oils and greases Dilute acids Dilute alkalies Ketones (MEK, acetone) Alcohols
Fluorocarbon (FPM)	Viton Fluorel	E. I. duPont de Nemours Co. Minnesota Mining & Mfg. Co.	Petroleum oils Di-ester base lubricants (MIL-L-7808, MIL-L-8085) Silicate-ester base lubricants (MIL 8200, MLO 8515, OS-45) Silicone fluids and greases Halogenated hydrocarbons (carbon tetrachloride, trichloroethylene) Selected phosphate ester fluids Acids
Isoprene-Synthetic (IR)	Ameripol SN Coral Natsyn Shell IR	Goodrich-Gulf Chemicals, Inc. Firestone Tire & Rubber Co. Goodyear Tire & Rubber Co. Shell Chemical Co.	
Polysacrylic (ACM)	Cyanacryl Hycar 1042 Polysar Thiacril	American Cyanamid Co. B. F. Goodrich Chemical Co. Krynac 880-Polymer Corp., Ltd. Thiokol Chemical Corp.	
Polysulfide	FA Polysulfide Rubber ST Polysulfide Rubber ZR-300 Polysulfide Rubber	Thiokol Chemical Corp. Thiokol Chemical Corp. Thiokol Chemical Corp.	Mixtures of petroleum solvents, ketones, and ethers
Silicone (Si)	Silastic No trade name No trade name	Dow Corning Corp. General Electric Union Carbide & Carbon	High-aniline point oils Dry heat Chlorinated di-phenyls
Fluorosilicone (FSi), IS		Dow Corning Corp.	

TABLE 3-19.
COMPARATIVE PROPERTIES OF COMMONLY USED ELASTOMERS

	Nitrile (Buna N)	Buna S (SBR or GRS)	Butadiene (BR)	Butyl (IIR)	Chloroprene (CR)	Chlorosulfonated Polyethylene (CSM)	Ethylene Propylene (EPM)	Fluorocarbon (FPM)	Isoprene (IR)	Natural Rubber (NR)	Polyacrylic (ACM)	Polysulfide	Polyurethane	Silicone (Si)	Teflon
Ozone resistance	P	P	P	GE	GE	E	E	E	P	P	E	E	E	E	E
Weather resistance	F	F	F	GE	E	E	E	E	F	F	E	E	E	E	E
Heat resistance	G	FG	F	GE	G	G	E	E	F	F	E	P	FG	E	E
Chemical resistance	FG	FG	FG	E	FG	E	E	E	FG	FG	P	G	P	EG	E
Oil resistance	E	P	P	P	FG	F	P	E	P	P	E	E	G	FG	E
Impermeability	G	F	F	E	G	G	G	G	F	F	E	E	F	P	G
Cold resistance	G	G	G	G	FG	FG	GE	F	G	G	P	G	G	E	E
Tear resistance	FG	FG	GE	G	FG	FG	GE	F	GE	GE	FG	P	GE	P	—
Abrasion resistance	G	G	E	FG	G	G	GE	G	E	E	G	P	E	P	E
Set resistance	GE	G	G	FG	F	F	GE	G	G	G	F	P	F	GE	P
Dynamic properties	GE	G	F	F	F	F	GE	GE	F	E	F	F	F	P	P
Acid resistance	F	F	FG	G	FG	G	G	E	FG	FG	P	P	P	FG	E
Reinforced tensile	GE	GE	E	G	G	F	GE	GE	E	E	F	F	E	P	—
Electrical properties	F	G	G	G	F	F	G	F	E	G	G	F	F	G	E
Water/steam resistance	FG	FG	FG	G	F	F	E	FG	FG	FG	P	F	P	FG	E
Flame resistance	P	P	P	P	G	G	P	E	P	P	P	P	P	F	G

E—Excellent G—Good F—Fair P—Poor —No reliable data

[From: *Seal Compound Manual*¹²³. Used by permission of Parker Seal Company.]

(14) *Silicone Rubber (Si)*

Temperature Range: -135° to 700°F (-93° to 371°C)

Silicone elastomers are made from silicone, oxygen, hydrogen, and carbon. They have poor tensile strength, tear resistance, and abrasion resistance. However, they have excellent resistance to temperature extremes, especially dry heat. Silicones are not resistant to petroleum liquids, but are resistant to many of the synthetic liquids.

(15) *Fluorosilicone (FSi)*

Temperature Range: -80° to 350°F (-62° to +176°C)

Fluorosilicone rubbers are a recent development and combine the good extreme temperature properties of silicone rubber with fuel and oil resistance.

3-6.2.2 Effect of Radiation on Elastomers, Plastics, and Resins

Seals, packings, and other similar components of hydraulic systems that use elastomers, plastics, or resins are subject to damage from radiation. As these components are usually the "weakest link" in the structure of a system, it is important to select materials that will provide the radiation resistance needed for a particular application. Data on the relative radiation resistance of elastomers, thermosetting resins, and thermoplastic resins are given in Figs. 3-57, 3-58, and 3-59 (Ref. 133).

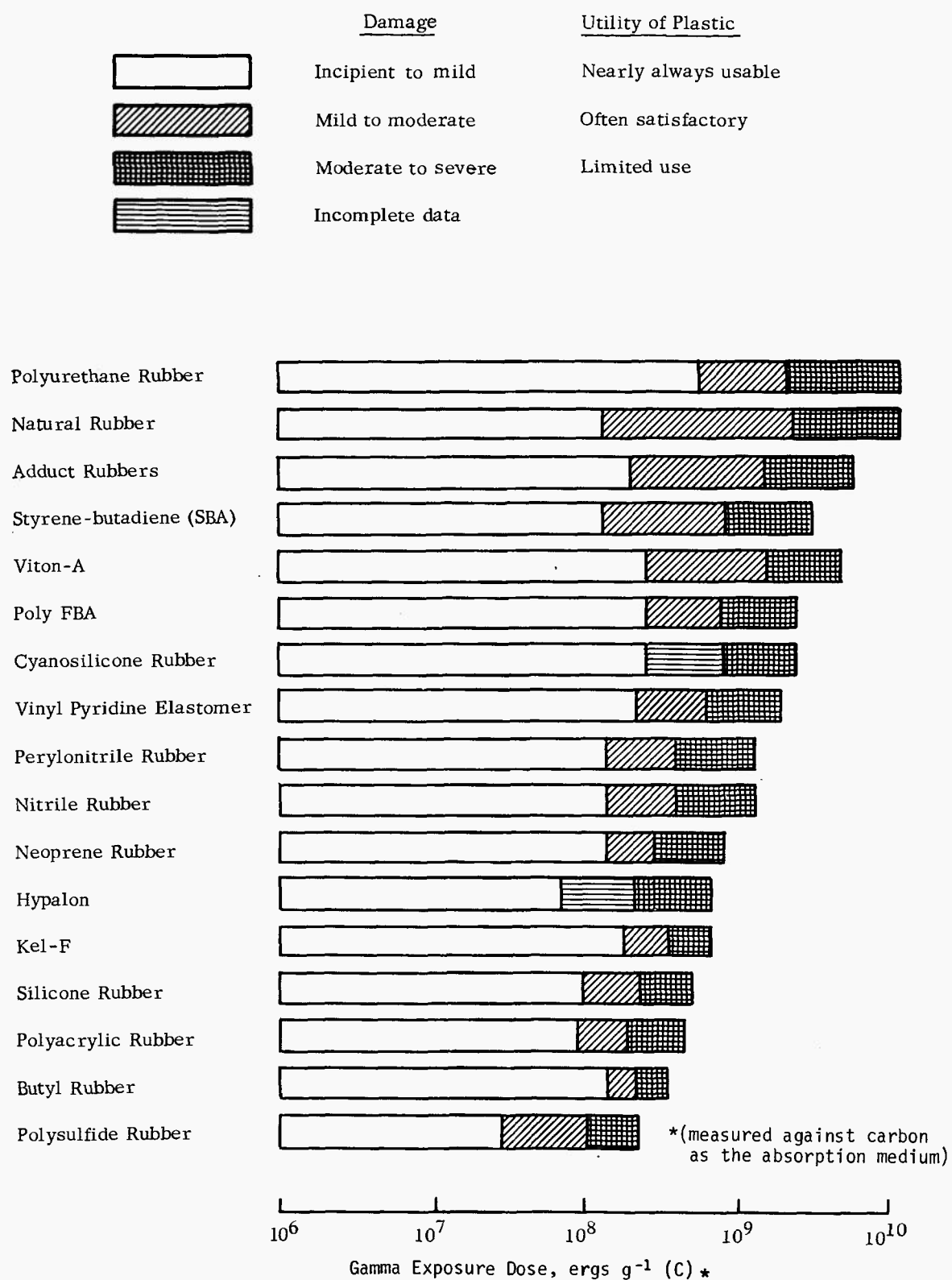
TABLE 3-20.
COMPATIBILITY OF COMMERCIAL HYDRAULIC FLUIDS WITH ELASTOMERS

Hydraulic Fluid	Dynamic and Static		Static Only												
	Ethylene Propylene Buna S	Nitrile Fluorocarbon	Polyacrylic Butyl Neoprene	Butadiene Hypalon Isoprene	Fluorosilicone Polyurethane Nat. Rubber	Silicone Polysulfide									
Phosphate Ester Liquids:															
Skydrol 500	1 4	4 4	4 2 4	4 4 4	3 4 4	3 4 4									
7000	1 4	4 2	4 1 4	4 4 4	3 4 4	3 4 4									
Pydraul F-9	2 4	4 1	4 2 4	4 4 4	2 4 4	2 X									
150	1 4	4 1	4 2 4	4 4 4	2 4 4	2 X									
625	2 4	4 1	4 2 4	4 4 4	2 4 4	2 X									
AC	2 4	4 1	4 2 4	4 4 4	2 4 4	2 X									
FRYQUEL (Cellulube) 90,															
100, 150, 220, 300, 500	1 4	4 1	4 1 4	4 4 4	2 4 4	1 4									
Houghto-Safe, 1010, 1055,															
1120	1 4	4 1	4 1 4	4 4 4	2 X 4	3 3									
MIL-H-19457B	1 4	4 2	4 1 4	4 4 4	4 4 4	3 4									
Halogen-Containing Liquids:															
Aroclor 1248 (a chlorinated biphenyl)	2 4	3 1	4 2 4	4 4 4	2 X 4	2 4									
Pydraul A-200 (chlorine-containing aromatic)	4 4	4 1	4 4 4	4 4 4	2 4 4	2 X									
FC-43, FC-75 (perfluorobutyl amines)	1 4	1 2	X 1 1	X 1 X	2 X X	1 1									
Silicate Ester Liquids:															
OS-45	4 4	2 1	X 4 1	4 2 4	2 4 4	4 X									
Oronite 8200, 8515	4 4	2 1	X 4 1	4 0 4	1 1 4	4 X									
MIL-H-8446B	4 4	2 1	X 4 1	4 X 4	1 1 4	4 X									
Silicone Liquids:															
Dow Corning 200, 510, F-60,															
F-61	1 1	1 1	1 1 1	1 1 1	1 1 1	3 1									
G.E. Versilube F-50	1 1	1 1	1 1 1	1 1 1	1 1 1	3 2									
Water Base:															
(Water-Glycol solutions)															
UCON Hydrolube	1 1	1 1	4 1 2	2 X X	2 4 X	1 X									
Houghto-Safe 271, 620	1 1	1 1	4 2 2	X X X	2 4 X	2 X									
(Water-oil emulsions)															
Sunsafe	4 4	1 1	4 4 2	4 2 4	1 4 4	X X									
Shell Iris 902	4 4	1 1	1 4 2	4 4 4	1 1 4	4 1									
Mineral Oils:															
MIL-H-5606B	4 4	1 1	1 4 2	4 2 4	1 1 4	4 1									
MIL-H-6083C	4 4	1 1	1 4 1	4 2 4	4 1 2	4 1									
MIL-H-27601A	4 4	1 1	1 4 2	4 X 4	2 X 4	3 X									

Compatibility Rating:

1 Satisfactory	3 Doubtful	X Insufficient Data
2 Fair	4 Unsatisfactory	G Good

[From: *Seal Compound Manual*¹³². Used by permission of Parker Seal Company.]

Fig. 3-57. Relative Radiation Resistance of Elastomers¹³³

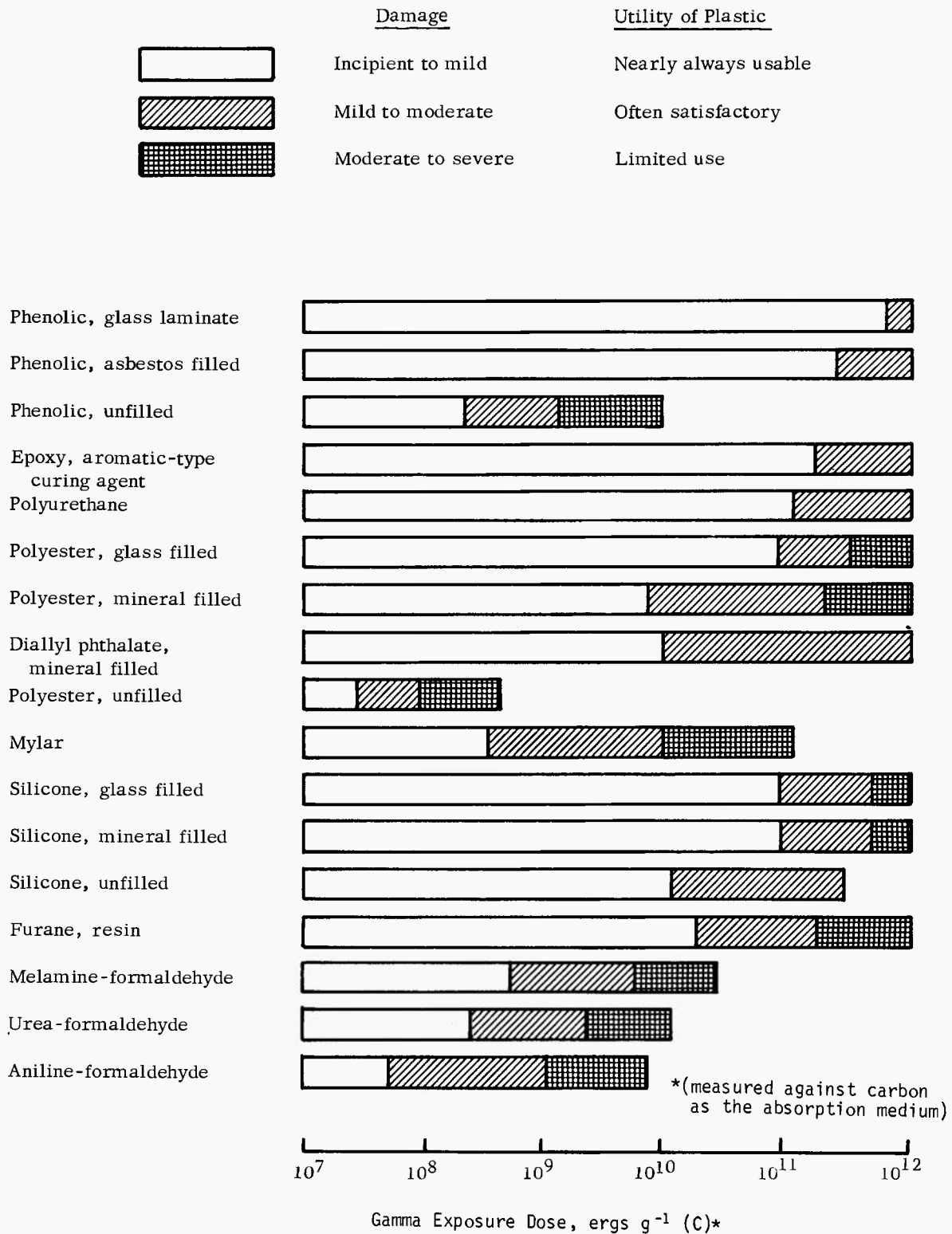
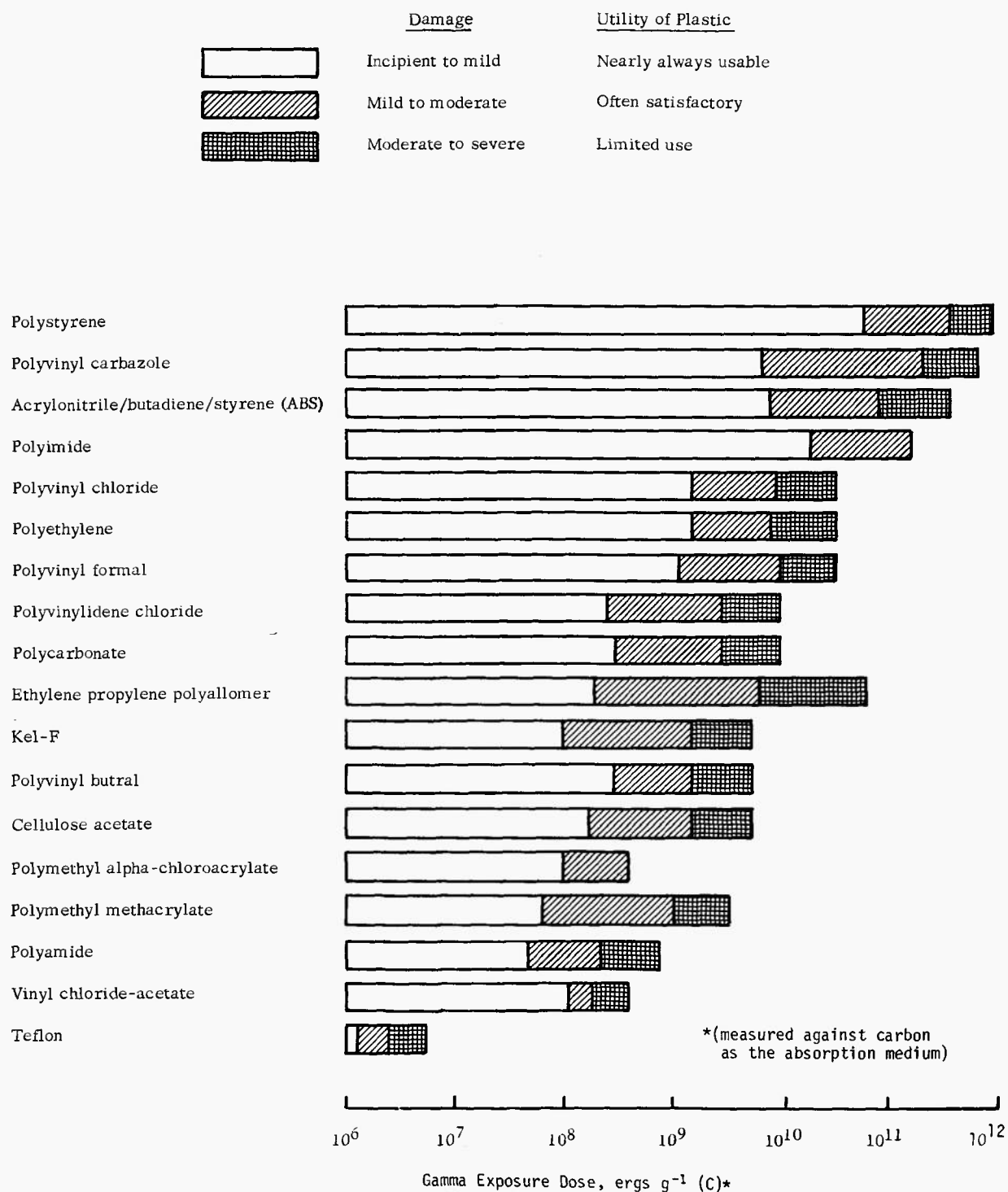


Fig. 3-58. Relative Radiation Resistance of Thermosetting Resins¹³³

Fig. 3-59. Relative Radiation Resistance of Thermoplastic Resins¹³³

3-6.2.3 Test Methods for Elastomer-liquid Compatibility

The usual procedure for determining the compatibility of an elastomer with a particular liquid is to measure changes in various properties of the elastomer after immersion in the liquid. The most commonly used indicators of deterioration of an elastomer compound are excessive volume swell or shrinkage, a large decrease or increase of hardness, and an extreme change in tensile strength or elongation. Many of the changes (such as loss of hardness and tensile strength) that various media cause in an elastomer compound cannot be considered a deterioration of the compound. Often such changes are purely physical and the compound returns to its original state after removal from the media. Also, certain changes, such as swelling of rubber, are often required for satisfactory operation of the system. Almost all seal designs require a definite amount of swelling to effect a complete seal. Table 3-21 lists the rubber swell requirements of several Military Specification hydraulic fluids.

Standard test procedures for various properties of elastomers can be found in ASTM Standards (Ref. 134). However, two general test methods have been developed specifically for the purpose of determining the effect of liquids on elastomers: (1) ASTM Test for

"Changes in Properties Resulting From Immersion in Liquids" (Ref. 135), and (2) Federal Test Methods for "Swelling of Synthetic Rubber" (Refs. 136, 137). These two test procedures are discussed in the paragraphs which follow.

(1) *Changes in Properties of Elastomers Resulting from Immersion in Liquids*

Test Method: ASTM D-471 (Ref. 135)

This method is intended for use in estimating the comparative ability of rubber and rubber-like compositions to withstand the effect of liquids by examination of the material after removal from the liquid.

This method leaves the selection of test conditions of temperature and time to the parties involved, but recommends the choice of one of eight test temperatures and one of four test periods. Three specimens of the elastomeric material are immersed in the liquid in a test tube for the time and at the temperature specified. After immersion, the specimens are examined for changes in weight, volume, tensile strength, elongation, and hardness. All changes are reported as a percentage of the original value.

(2) *Swelling of Synthetic Rubbers*

Test Methods: Federal Test Method 3603 (Ref. 136)

Federal Test Method 3604 (Ref. 137)

These test methods describe a procedure for the determination of the swelling effect of lubricants on synthetic rubber. Method 3603 is for petroleum

TABLE 3-21.
RUBBER SWELL REQUIREMENTS OF MILITARY
SPECIFICATION HYDRAULIC FLUIDS

Military Specification	Test Method or Test Description	Type of Rubber	Required Rubber Swell, %	
			Min	Max
MIL-H-5606B	Federal No. 3603.4*	Standard L	19.0	28.0
MIL-H-6083C	Federal No. 3603.4*	Standard L	19.0	26.5
MIL-H-13866A	168 hr at 158°F	Standard L	—	25.0
MIL-H-27601 A	70 hr at 400°F	Viton A or B	0	10.0
<i>Phosphate Ester</i> MIL-H-19457B (SHIPS)	Federal No. 3603.4*	Butyl	± 5% of swell caused by tricresyl phosphate	
<i>Silicate Ester</i> MIL-H-8446B	Federal No. 3603.4*	Synthetic S	15.0	25.0

*Federal Test Method Standard No. 791a.

products in general, and Method 3604 is for aircraft turbine lubricants. The basic procedures of the test methods, however, are adaptable to other products.

The volume of standardized test rubber sheets (1 in. x 2 in. x 0.075 in.) is determined by water displacement. The rubber sheets are then immersed in the specimen liquid for 168 hr at 158°F. The rubber sheets are then removed, cleaned, and the volume again determined by water displacement. Any change in volume is presented as a percent of the original volume.

3-6.3 COMPATIBILITY WITH COATINGS

Compatibility of hydraulic fluids with paints and other surface protection coatings is a problem that is often ignored in early design stages. Although it may have been previously determined that a candidate hydraulic fluid is compatible with the materials used in the system, it is still necessary to determine compatibility with surface coatings it may contact. The number and types of coatings are many—painted, anodized, phosphatized, nitrided, and plated.

3-6.3.1 Compatibility With Paints

Paints are probably the most common surface coatings encountered. Although paints are normally exterior to the hydraulic system (except in rare cases where reservoirs or other components have their interior surfaces painted), their compatibility with hydraulic fluids must be considered. Hydraulic fluids can come into contact with painted surfaces from spillage during filling, from leaks, and from rupture of hydraulic lines.

Many of the synthetic liquids have a softening or stripping action on paints that are resistant to petroleum oils and fuels. Phosphate ester fluids, commonly used in commercial aviation, have a marked stripping action on conventional paints. Water-glycol solutions also have a softening and stripping action on many paint finishes. For these and other synthetic hydraulic fluids, the more resistant synthetic finishes must be employed, e.g., epoxy-resin paints. The effect of various types of hydraulic fluids on standard oil and fuel resistant paints is summarized in Table 3-22. The data presented in Table 3-22 are generalized and in every case, compatibility of a particular paint should be checked with the candidate hydraulic fluid. Workers at the U.S. Army Coating and Chemical Laboratory have done research on the compatibility of various hydraulic fluids with Military Specification paints. The results of

some of this work are shown in Table 3-23. Hydraulic fluid manufacturers frequently have proprietary data available on compatibility of their products with special paints or finishes and will supply the data to purchasers.

TABLE 3-22.
EFFECT OF HYDRAULIC FLUIDS
ON STANDARD PAINTS*

Hydraulic Fluid Type	Effect on Paints
Mineral Oils	None
Water-glycols	Softens or strips
Water-oil Emulsions	None
Chlorinated Aromatics	Incompatible
Phosphate Esters	Incompatible
Silicones	Incompatible

**Standard paints are petroleum fuel- and oil-resistant.*

The resistance of various types of paints to attack by chemical media is given in Table 3-24. The data presented in Table 3-24 are not directly applicable to hydraulic fluids, but can be useful in determining what effect various contaminants or additives may have on the compatibility of hydraulic fluid with paints.

3-6.3.2 Compatibility With Other Coatings

The compatibility of hydraulic fluids with surface coatings other than paints is an area that has received very little attention. Other surface coatings would include metal platings, anodizing, nitriding, and phosphate finishing. There are essentially no data available on these topics either in the general literature or on hydraulic fluid manufacturers' data sheets.

The lack of data could lead to the conclusion that compatibility with these surface finishes is not a problem. However, because these finishes are either metallic or a chemical conversion of the base metal, the question is one that should be considered in the determination of liquid-metal compatibility.

3-6.4 COMPATIBILITY WITH OTHER LUBRICANTS

Compatibility of a hydraulic fluid with other lubricants it may contact must also be considered. Other lubricants include substitute hydraulic fluids, lubricating

TABLE 3-23.

RESISTANCE OF MILITARY SPECIFICATION COATINGS TO HYDRAULIC FLUIDS*

Coating Specification	Title	Liquids or Hydraulic Fluids the Coating Resists
MIL-L-19537A	Lacquer, Acrylic-Nitrocellulose, (for Aircraft Use)	Diester Lubricating Oils
MIL-L-19538B	Lacquer, Acrylic-Nitrocellulose Camouflage (for Aircraft Use) (ASG)	MIL-L-7808G, Synthetic Base Lubricating Oil
MIL-C-22750B	Coating, Epoxy-Polyamide	Diester Lubricating Oils
MIL-P-22808A	Paint, Epoxy, Hydraulic Fluid Resistant	MIL-E-17111, Petroleum Base Power Transmission Fluid MIL-H-19457B, Phosphate Ester Fluids
MIL-P-23377B	Primer Coating, Epoxy Polyamide Chemical and Solvent Resistant	Diester Lubricating Oil
MIL-L-7146A	Lacquer, Hydraulic Fluid Resistant (for Interior Aircraft Use)	MIL-H-5606B, Petroleum Base Hydraulic Fluid MIL-H-22072 (AER), Water Base Hydraulic Fluid

**Data obtained in private communication with Dr. C.F. Pickett, Director, U.S. Army Coating and Chemical Laboratory, 26 Aug. 68.*

oils, greases, and solid film lubricants. Most hydraulic systems in operation today use components not lubricated by the hydraulic fluid. For the system to operate satisfactorily, it is essential that the hydraulic fluid be compatible with any of these lubricants it may contact, either accidentally or by design.

Compatibility of one hydraulic fluid with another is a problem that does not occur often and so it is frequently forgotten. The problem is primarily of concern in replacing one hydraulic fluid with another. When nonadditive petroleum hydraulic fluids were the only ones available, changing to another hydraulic fluid was an easy matter. However, the advent of extensive use of additives and the synthetic liquids made substitution of hydraulic fluids virtually impossible. Many of the synthetic fluids are completely incompatible with one another or with petroleum fluids. Upon mixing, even in small ratios, they may form precipitates, gums, sludges, or gels. Water and oil emulsions are often compatible with mineral oil fluids in the sense that they will tend to absorb small amounts of the oil into the emulsion. Reduction of the fire retarding properties is the only resulting harm. Several Military Specification hydraulic fluids have requirements that they be compatible

with certain other fluids in the sense that they do not separate or form gums, precipitates, or gels. However, this requirement may have the effect of deactivating important additives or the loss or reduction of important properties.

There are no standard ASTM or Federal Test Methods available for directly determining the compatibility of one hydraulic fluid with another. Simple mixing tests with visual observation to determine separation, emulsification, formation of solids, etc., are normally used to screen for compatibility. However, there are standard test methods to determine the compatibility of lubricating oils and solid film lubricants with hydraulic fluids. Two of them are discussed in the paragraphs which follow.

(1) *Compatibility of Turbine Lubricating Oils*

Test Method: Federal Test Method 3403 (Ref. 138)

This method is used to determine the compatibility of aircraft turbine lubricants with specific referee lubricants. Although the test procedure is designed for aircraft turbine lubricants, it can be used to test the compatibility of hydraulic fluids with any referee liquid.

TABLE 3-24.

RESISTANCE OF PAINTS TO ATTACK BY CHEMICAL MEDIA

Chemical Media	Alkyd	Acrylic	Bituminous	Cellulose	Epoxy	Phenolic	Polyester	Vinyl	Vinyl-Alkyd (1:1)	Chlorinated Rubber
Salt Spray	G-E	E	E	E	E	E	E	E	E	E
Alcohol Solvents	F-G	P	P	G	G-E	E	G	F	G	E
Gasoline	G-E	G	P	G	E	E	E	E	E	G
Hydrocarbon Solvents	G-E	F	P	F	E	E	E	—	—	—
Ester, Ketone Solvents	P	P	P	P	G-E	F	P	P	P	P
Chlorinated Solvents	P	P	P	P	G-E	F	P	P	P	P
Alkalis	F-G	F-G	E	P	E	P	P	E	F-G	E
Mineral Acids	P-G	F-G	F-G	F-G	G-E	P-F	E	E	G-E	E
Oxidizing Acids	P-F	P-F	—	P	P-G	P-F	P	E	P	G
Organic Acids (Acetic, Formic)	P	P	E	P	F-G	P	P	G	F-G	F-G
Organic Acids (Oleic, Stearic)	F	F	P	F	E	E	F	E	E	F
Phosphoric Acids	P	P	E	G-E	G-E	F	F	E	F	G
Water	F-G	E	E	G	E	E	F	E	E	E
P-Poor F-Fair G-Good E-Excellent										

[From: *Materials Engineering, Materials Selector Issue*¹⁴¹. Used by permission of Reinhold Publishing Corp.]

Three mixtures of 200 ml are prepared with the test liquid and the referee liquid. Mixtures are of 20, 100, and 180 ml of referee fluid. The mixtures are agitated by vigorous shaking and then heated to 212°F for 168 hr. The mixtures are then cooled, agitated again, and centrifuged (at 600 to 700 relative centrifuge force) for 10 min. The amount of sediment, if any, is recorded. The test temperature and mixture ratios can be changed to fit the type of fluid being tested.

(2) *Fluid Resistance of Dry Solid Film Lubricants*

Test Method: Federal Test Method 7001 (Ref. 139)

This method determines the resistance of dry solid film lubricants to loss of adhesion after exposure to

various fluids. A 0.0002 - 0.0005 in. thick film of the solid lubricant is sprayed on both sides of a 3 in. by 6 in. anodized aluminum panel and cured. Two test panels with solid film lubricant are immersed one-half their length in a test fluid at 73.5°F (23°C) for 24 hr. The panels are then cleaned with naphtha and examined for softening, lifting, blistering, cracking, or peeling. A test of lubricant adhesion is made by pressing a strip of masking tape on the dry film lubricant and removing it rapidly.

The test fluids listed in the procedure are aircraft turbine oil (MIL-L-7808), standard hydrocarbon test fluids (MIL-S-3136, Type II), aircraft engine lubricating oil (MIL-L-6082, grade 1100), aircraft reciprocating

engine fuel (MIL-G-5572, Grade 115/145), aircraft turbine and jet fuel (MIL-T-5624, JP-4) and petroleum base hydraulic fluid (MIL-H-5606B). The general procedure of the test method, however, is adaptable to any fluid desired.

3-6.5 COMPATIBILITY WITH ADDITIVES

Liquids for fluid power systems may contain additives to improve the viscosity index, to suppress the formation of foam and emulsions, to combat corrosion, etc. If the proper chemicals are not used, one additive may counteract the desired effects of another, or may react with another to form insoluble substances that could be more harmful than the original problem. Additives must remain soluble in the fluid at all exposed temperatures and should not react with component parts or contaminants. Chemicals must not be indiscriminately mixed with an oil. Hydraulic fluid suppliers should be consulted on special problems. Additives are discussed in greater detail in Chapter 5.

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CHAPTER 4

TYPES OF HYDRAULIC FLUIDS

4-1 GENERAL

As the use of hydraulics and fluid power systems has increased, the number and types of hydraulic fluids available have also increased. This chapter presents a description of several methods used to classify hydraulic fluids. In addition, descriptions of the more common types of hydraulic fluids are presented with a brief summary of specifications for each type of fluid and specification data sheets listing exact specification requirements for every hydraulic fluid discussed. These specification summaries and data sheets are presented at the end of the chapter.

4-2 CLASSIFICATION OF HYDRAULIC FLUIDS

A wide range of liquids is available for use in hydraulic systems, and it is desirable to employ a classification system to assist those using hydraulic fluids to determine if a liquid under consideration may function satisfactorily for a particular application. However, the task of selecting the most meaningful classification system is complicated by several factors. The areas of application of hydraulic systems and the type of equipment used have become so diverse that a classification useful in one area of application has little or no meaning in another. In addition, the increasing number and types of hydraulic fluids available add to the complexity of the task. In simple, low performance hydraulic systems, where operating parameters are not severe, almost any liquid—water, water-based liquids, natural petroleum products, or the more sophisticated synthetic liquids—may be used with varying degrees of satisfaction. In other areas, where the operating parameters are very severe, only a limited number of liquids may be considered and selection must be made with considerable care. In addition, there are liquids which are used primarily for purposes other than as hydraulic fluids, but which have properties permitting them to be employed for the latter purpose in many applications.

Because of the wide and vastly different areas of application, it is not surprising that hydraulic fluids have been classified by many different systems based on their different characteristics such as physical properties, chemical types, operating capabilities, utility, or specific applications. Although none of these groupings fully describe the properties of a hydraulic fluid, they are still employed and assist in selecting fluids for use in specific areas.

4-2.1 CLASSIFICATION BY PHYSICAL PROPERTIES

A classification based on viscosity ranges was one of the earliest methods used since petroleum products were the only hydraulic fluids widely used and viscosity was the most important property of this class of hydraulic fluids. The viscosity method is accepted and used as a means of classifying petroleum base hydraulic fluids by the fluid manufacturers, the automotive industry, hydraulic component manufacturers, and hydraulic system designers and builders. Hydraulic fluids grouped in this manner are generally specified as suitable for use in a given application within a specified viscosity range. However, in the case of nonpetroleum base synthetic fluids, a classification based on viscosity range alone is not sufficient because of the importance of other properties.

4-2.2 CLASSIFICATION BY CHEMICAL PROPERTIES

Chemical classification of hydraulic fluids is extensively used by technical personnel, such as chemists and petroleum engineers. Chemical classification assists them in predicting general characteristics of a new hydraulic fluid or in developing a new hydraulic fluid for a specific application. In chemical compounds such

as hydraulic fluids, the physical properties are dependent upon the compound structure and, accordingly, the physical properties of two chemically similar fluids may not be the same. Within a given class of hydraulic fluids where the chemical properties are similar, the physical properties of these fluids may vary greatly.

4-2.3 CLASSIFICATION BY OPERATING CHARACTERISTICS

When classifying hydraulic fluids according to operating characteristics, the most common operational parameters used are the temperature limits and the fire-resistant characteristics of the hydraulic fluid. The aerospace industry and the Air Force are the principal users of the classification system based on operational temperatures and have established the following system types:

- (1) Type I.—65° to 160°F
- (2) Type II.—65° to 275°F
- (3) Type III.—65° to 400°F
- (4) Type IV.—65° to 550°F
- (5) Type V. 0° to 700°F
- (6) Type VI. +40° to 1,000°F (Proposed)

Although this classification system has proved valuable and useful to some users, it does not identify other properties of the liquids and one type may include several chemical classes. Type I liquids include some petroleum hydrocarbons, phosphate esters, silicate esters, emulsions, water-base liquids, polyalkylene glycols, and halogenated hydrocarbons. Type II liquids include petroleum hydrocarbons and silicate esters. Type III liquids include the deep dewaxed highly refined hydrocarbons, synthetic hydrocarbons, silicate esters, and silicones. Type IV liquid requirements have not been fully met by any class of fluids. However, the deep dewaxed highly refined mineral oils covered under MIL-H-27601A (-40° to +550°F) closely approach the Type IV requirements. Type V and VI fluids have not been completely defined or tested. Some potential candidate fluids for Type V are polyphenyl ethers, perfluoroalkylesters, and specially refined hydrocarbons. Liquid metals have some potential for satisfying Type VI requirements.

In general, there are commercial hydraulic fluids readily available which operate satisfactorily over the temperature ranges of Types I, II, and III hydraulic systems. However, for the higher temperature ranges of Types IV, V, and VI, only a limited number of fluids are available and those are usable only for relatively short durations. Extensive research programs are being conducted to develop fluids (and components) which will be usable in Types IV, V, and VI hydraulic systems.

Classification of hydraulic fluids and systems based on operational temperature ranges is not satisfactory in many cases, such as in industrial systems, since there is no need for a -65°F operational temperature requirement. However, it is important that every hydraulic fluid have a definite operational temperature range established. Knowledge of these temperature limits is necessary in selecting a hydraulic fluid for a specific application.

4-2.4 CLASSIFICATION BY FIRE RESISTANCE

Hydraulic fluids can be classed as flammable or fire-resistant. However, this classification is somewhat arbitrary since the degree of flammability depends on both the specific fluid and the definition of "flammability". Generally, fire-resistant hydraulic fluids are of three types—synthetic fluids, water-based fluids, and emulsions. Fire-resistant synthetic fluids are fire-resistant because of their chemical nature and include phosphate esters, chlorinated hydrocarbons, halogen-containing compounds, organophosphorus derivatives, and mixtures of similar materials. The water-base fluids are solutions of various natural or synthetic materials in water, and depend upon their water content for fire-resistance. Glycols, polyglycols, and mixtures containing additives are the most common hydraulic fluids of this type. Emulsion-type hydraulic fluids also depend upon water content for fire-resistance and are water-in-oil mixtures made from petroleum hydrocarbons, but may contain various additives to provide other desirable properties.

4-2.5 CLASSIFICATION INTO PETROLEUM OR NONPETROLEUM HYDRAULIC FLUIDS

One of the most widely used classifications of hydraulic fluids is based on a separation into two general classes—petroleum and nonpetroleum. However, the petroleum class hydraulic fluids may contain additives, even synthetic additives, without changing their classifications. The nonpetroleum and/or synthetic class of hydraulic fluids includes a considerably wider range of liquids since it contains those derived from nonpetroleum base liquids (water, castor oil) as well as the synthetic base liquids produced by major chemical reactions, although the base material for some of these liquids may be a petroleum product.

4-2.6 CLASSIFICATION USED IN THIS HANDBOOK

The classification system used in this handbook combines the two classification systems described in pars. 4-2.2 and 4-2.5. The major division in this classification is petroleum base and nonpetroleum and/or synthetic base. However, the latter category is subdivided into chemical classes to aid in identifying the wide range of properties of these hydraulic fluids.

Comparative or relative ratings of some of the general characteristics of the different classes of hydraulic fluids are shown in Table 4-1. It must be remembered that these ratings are only a general overall rating of the hydraulic fluid base stock in each class and that wide variation may be found in specific liquids particularly when additives are used.

A description of general properties and characteristics of the different classes of hydraulic fluids is given in subsequent paragraphs. Included at the end of the chapter are summaries and specification data of Military or Government Specifications for typical liquids in the respective classes (see par. 4-6). Requirements such as composition, usable temperature range, and typical usage are listed. There are specifications for hydraulic fluids other than those listed. No attempt was made to list specifications for all liquids or oils which could be used as hydraulic fluids. The hydraulic fluids and lubricants selected are those which are most widely used or those which represent the range of properties in specific classes of hydraulic fluids. It should be remembered that the specification values are only limiting values and that specific hydraulic fluids may differ considerably from these values. Also, it should be noted that there are many nonspecification hydraulic fluids, in all classes, which may have properties equal or superior to the specification values.

4-3 PETROLEUM BASE HYDRAULIC FLUIDS

Petroleum base hydraulic fluids were among the first liquids employed as hydraulic or power transmission fluids. The use of petroleum base hydraulic fluids far surpasses that of all other classes including the synthetics and nonpetroleum classes. However, the wide variety of materials produced from different grades of crude oils and additives makes a summary of their properties difficult. In general, these fluids are considered to give outstanding performance, long life, good lubricating characteristics, and protection against rust,

oxidation, corrosion, sludge, and foam formation. Of course, not all fluids in this class will have all of these characteristics but, through selection of the proper grade of petroleum base fluid and additives, the desired properties may usually be obtained. These fluids generally have a high viscosity index (approximately 100) so that they may be used over a wide temperature range. They have pour points as low as -90°F and flash points as high as 400°F. Fire point of these fluids generally ranges from 400° to 550°F. Viscosity and viscosity-temperature characteristics vary over a wide range.

Most petroleum and many chemical manufacturing companies market a large number of petroleum base hydraulic fluids, and these companies can provide information on specific properties or applications of their products. There are numerous Military or Government Specifications covering different types of petroleum base hydraulic fluids. Some of the more widely used liquids are described in the specification summaries and specification data sheets in par. 4-6.

4-4 NONPETROLEUM BASE HYDRAULIC FLUIDS

4-4.1 PHOSPHATE ESTERS

This class of hydraulic fluids results from the incorporation of phosphorus into organic molecules. The resulting compounds have properties making them useful as hydraulic fluids. They can also be used as a base stock fluid, as a part of the base stock, or as an additive. The principal advantage of this class of hydraulic fluids over petroleum base hydraulic fluids is that many of the compounds are not only excellent lubricants but also have excellent fire-resistant properties. They have good oxidation stability and their thermal stability is considered good at medium-high temperatures, but they begin to deteriorate rapidly above 300°F. Hydrolytic stability ranges from poor to very good depending upon individual compounds. Viscosity-temperature characteristics of most phosphate esters are considered medium-to-good. In this respect they are equivalent to the better petroleum base hydraulic fluids but are not as good as the best petroleum products. Viscosity of the phosphate ester hydraulic fluids is generally low and, on an equivalent volatility basis, their viscosity characteristics are superior to petroleum base products. Some phosphate esters can be used as a mild extreme pressure lubricant.

TABLE 4-1.
CHARACTERISTICS OF HYDRAULIC FLUID BASE STOCKS

Fluid Class	Viscosity- temperature	Volatility- viscosity	Thermal Stability	Oxidative Stability	Hydrolytic Stability	Fire Resistance	Lubricating Ability	Additive Response
I. Petroleum Base	G	P	G	F	E	P	F	E
II. Nonpetroleum Base								
A. Phosphate Esters	G	F	F	G	F	E	E	G
B. Silicate Esters	E	G	E	G	F	F	G	G
C. Carboxylic Acid Esters	G	G	F	F	G	F	G	G
D. Polysiloxanes	E	E	G	F	E	F	P	P
E. Glycols	G	G	G	G	G	F	G	F
F. Castor Oils	G	G	F	F	G	F	G	G
G. Polyoxy Glycols	G	G	G	G	G	F	G	F
H. Water Glycols	G	P	F	G	E	E	P	G
I. Emulsions	G	P	F	G	E	E	P	G
III. Experimental and Potential Fluids								
A. Polysiloxanes (Silanes)	F	F	E	G	E	F	F	F
B. Hydrocarbons	G	G	E	F	E	P	G	G
C. Fluorinated Polymers	P	P	E	E	G	E	P	P
D. Polyphenyl Ethers	F	G	E	G	E	F	G	G
E. Heterocyclic Synthetics	-	-	G	-	-	G	-	-
F. Phosphonitrilates	F	G	W	E	W	G	E	G
G. Liquid Metals	G	F	G	P	P	P	F	F

E Excellent

G Good

F Fair

P Poor

W Wide Range Variable

- Not Defined

The MIL-SPEC requirements for a typical phosphate ester base hydraulic fluid are shown in the summary and specification data sheets in par. 4-6.

4-4.2 SILICATE ESTERS

This class of hydraulic fluids has many properties similar to the phosphate esters since both are esters of organic acids. The principal differences in the two classes are in hydrolytic stability, lubricating characteristics, flammability, and viscosity-temperature relationships. In general, silicate esters have low volatility and excellent viscosity-temperature characteristics, but relatively poor hydrolytic stability. One of the outstanding characteristics of this class of hydraulic fluids is good thermal stability combined with excellent response to antioxidant additives. Silicate esters possess only fair oxidation stability and are similar to hydrocarbon hydraulic fluids in their susceptibility to attack by oxygen; however, it is relatively easy to improve this property with proper additives. The lubricating properties of silicate esters are only fair but with care in selection of materials and operating conditions, these hydraulic fluids will provide some degree of lubrication. Silicate esters are generally fairly good solvents and, although they do not dissolve many plastics or synthetic elastomers, they tend to harden most elastomers after prolonged exposure at elevated temperatures. With proper additives and the right operating conditions, some silicate ester hydraulic fluids operate satisfactorily for extended periods at temperatures up to 425°F.

In addition to their use as hydraulic fluids, silicate esters are used as heat-transfer fluids, electronic equipment coolants, weapon lubricants, etc. because of their outstanding thermal stability and excellent response to antioxidants. A typical MIL-SPEC for a silicate ester aircraft hydraulic fluid is given in the summary and the specification data sheets in par. 4-6.

4-4.3 ORGANIC ACID ESTERS

This class of liquids is employed principally as lubricants for gas turbine engines, instrument lubricants, base stock for synthetic greases, and, to a limited extent, as a base stock for hydraulic fluids. Use as a hydraulic fluid is generally in applications where engine lubricating oil is used to actuate hydraulic units such as accessories attached to jet engines.

Organic esters are produced in both monoester (single ester group) and diester (two ester groups per molecule) compounds. The monoesters have relatively good

lubricating properties. However, they allow fairly high wear because of low shear strength, high volatility, and susceptibility to oxidative breakdown. For these reasons, the monoesters have little or no applications as hydraulic fluids. On the other hand, the diesters have excellent viscosity-temperature properties, low volatility, good lubricating characteristics, high chemical solvency, good additive response, and good hydrolytic stability. The diester lubricating film characteristics and oxidation stability are generally equal to or better than equivalent petroleum hydrocarbon fluids. The principal restriction or limitation of organic ester liquids is thermal stability since they tend to break down at temperatures above 500°F.

The MIL-SPEC requirements for typical organic acid esters are given in the summary and data sheets in par. 4-6.

4-4.4 POLYSILOXANES

The silicone liquids, as a class, possess very good viscosity-temperature and mechanical properties, making them attractive as base stocks for synthetic lubricants or as hydraulic fluids. These liquids have been used as hydraulic fluids, either alone or as compounded hydraulic fluids. Other characteristics which make the silicone liquids ideal for hydraulic fluids under severe operating conditions are: (1) their properties do not change appreciably under a wide range of temperature and atmospheric conditions, (2) they have very low volatility, (3) they are compatible with many construction materials, (4) they resist permanent viscosity change under severe mechanical stresses, (5) they are available in a wide range of viscosities, (6) they have very good dielectric properties, (7) they have good oxidation resistance, and (8) they have low chemical solvency properties. These liquids are also less flammable than petroleum oils of similar viscosities but do not resist ignition in many flammability tests. Significant limitations of silicone liquids are their marginal lubricity for ferrous materials in sliding contact and their high compressibility. In general, the serviceable temperature of most silicone fluids ranges from well below -65° to above 400°F.

Summaries of Federal and MIL-SPEC requirements for typical silicone fluids and data sheets for these specifications are in par. 4-6.

4-4.5 GLYCOLS

This class of hydraulic fluids is frequently referred to by several names including polyglycols, polyalkylene

glycols, and polyethers. These glycol or polyglycol liquids are used extensively as base stocks and as components for synthetic lubricants and hydraulic fluids such as air conditioner lubricants, heavy duty brake fluids, and components of fire-resistant water-base hydraulic fluids. These liquids are characterized by good lubricity and antiwear properties, high flash point, high viscosity indices (up to 150), wide range of viscosities, low volatility and pour point, poor-to-fair high temperature oxidation properties, little effect on rubber and metals, and very good solubility characteristics and additive response. They have good resistance to sludge and varnish formation, and excellent resistance to mechanical shear. The viscosity-temperature properties are equal to or better than similar petroleum products. In general, the serviceable temperature range of these fluids is from near 0° to above 500°F.

MIL-SPEC requirements for a typical glycol type hydraulic fluid are given in the summary and specification data sheets in par. 4-6.

4-4.6 CASTOR OILS

This class of hydraulic fluids is based on organic fatty oils similar to animal oils, fish oils, and mineral oils. Because of their properties, they are seldom used alone as a lubricating oil or hydraulic fluid. The organic oils oxidize, causing gumming, and they spoil or become rancid, thus releasing free fatty acids. At high temperature, these oils tend to decompose to corrosive acids. These oils also will support bacteria and care should be taken to keep them sterile. The addition of castor oil or other fatty oils to petroleum mineral oils will increase the load-carrying ability. Some of the liquids incorporating these oils are steam-cylinder oils, marine-engine oils, cutting oils, automatic-transmission fluids, hydraulic fluids, and industrial gear oils. In general, castor oils are moderately high viscosity liquids with a flash point above 500°F and a pour point above 0°F.

Summary and data sheets of several typical MIL-SPEC requirements for compounded liquids containing castor oil are in par. 4-6.

4-4.7 POLYOXYALKYLENE GLYCOLS

The polyoxyalkylene glycol class of hydraulic fluids have many of the same properties as the polyalkylene glycol liquids discussed in par. 4-4.5. In some cases, the polyoxyalkylene liquids have somewhat superior properties. Most of these fluids have a polyoxyethylene-

polyoxypropylene base and are characterized by high viscosity indexes, low pour points, good thermal stability, fair-to-good oxidation stability, good water tolerance, good corrosion resistance, and compatibility with rubber and other materials in brake systems. These liquids are considered particularly useful as hydraulic fluids for automotive brake systems.

A summary of MIL-SPEC requirements for a brake fluid containing this class of liquid and a data sheet of specification properties are in par. 4-6.

4-4.8 WATER GLYCOLS

This class of hydraulic fluids is generally considered fire-resistant. It usually contains 35-60 percent water, a glycol, and a water-soluble thickener to improve viscosity. Additives are also incorporated to improve anti-corrosion, antiwear, and lubricity properties. Since the fire-resistance properties of these liquids are dependent upon the water content, extended use at temperatures above 150°F is not recommended. The viscosity of these liquids is fairly low, but with proper additives they may be used satisfactorily at fairly low operating temperatures in systems such as aircraft hydraulic systems. Typical viscosity indices for these liquids are in the range of 140 to 160. Because of the corrosive nature of the water component of these liquids, proper additives must be used to make them compatible with most common construction materials such as steel, aluminum, brass, and copper. It is generally not good practice to use these liquids in contact with soft or sacrificial plated materials such as galvanizing or cadmium plating. Antiwear and lubricity additives can make these liquids suitable for use in hydraulic systems and machines at moderate pressures. However, at high pressures or loads, service and maintenance problems increase. The additive-containing water-glycol liquids generally are compatible with the various seal and packing materials used in systems designed for petroleum type fluids, but these aqueous-base liquids tend to soften or lift many conventional paints or coatings. In general usage, it is a good practice to conduct periodic checks of water content of these liquids since the viscosity and other properties vary appreciably with the water content.

MIL-SPEC requirements for a typical water-glycol type hydraulic fluid are given in the summary and specification data sheets in par. 4-6.

4-4.9 EMULSIONS

These water-oil mixtures are another class of liquid which depend upon water content for their fire-resistant properties. These liquids, which have many characteristics similar to the water-glycol liquids, are available in two general types—oil-in-water or water-in-oil. The first of these has water as the continuous phase and the oil is present in lesser amounts as the dispersed media. Many problems are associated with the water phase—including corrosion in both the liquid and vapor phase, and high wear because of poor lubricating characteristics. The other type of emulsion, the water-in-oil mixture in which the oil is the continuous phase and the water is the dispersed media, has considerably different and generally better characteristics. These emulsions have good-to-acceptable corrosion and lubricating properties as well as fire-resistance, emulsion stability, high viscosity index, film strength, good system cooling, compatibility with most materials, oxidation stability, and reasonable material cost.

Water-in-oil emulsions do not have high load capacity or lubricating characteristics but where fire resistance is needed for safety, these liquids can be applied. The usable temperature range of these liquids is generally between 0° and 150°F. However, they may be used somewhat beyond this range. At this time, there are no MIL-SPEC requirements covering this class of fluids; however, there are several commercial products that are widely used.

4-5 NONSPECIFICATION AND POTENTIAL HYDRAULIC FLUIDS

4-5.1 PETROLEUM BASE FLUIDS

Most petroleum and many chemical companies produce hydrocarbon or petroleum base hydraulic fluids which are not qualified under Military or Federal Specifications. However, many of these liquids have properties generally similar to the specification liquids and are useful in hydraulic system applications. The list of these products and manufacturers is too extensive to list in this handbook, and it is recommended that individual manufacturers be contacted for information concerning properties and applications of a specific hydraulic fluid.

Many petroleum manufacturers have extensive programs directed toward the development of improved

petroleum base hydraulic fluids. Improvements sought are in the area of extended operating temperature range, fire resistance, improved thermal and oxidative stability, better viscosity-volatility characteristics, better response of susceptibility to inhibitors and additives, and better low temperature fluidity. Improvements are being obtained by a combination of several procedures including chemical conversion of selected mineral oil fractions such as (1) hydrocracked naphthenes, (2) isomerized wax, (3) alkylated aromatics, and polymerized olefins; use of advanced refining techniques (super-refining, vacuum fractionation, deep dewaxing) on selected crude stocks; and a selection of improved inhibitors and additives. Petroleum fractions have been produced that are capable of extended use at temperatures up to 650°F, and with a useful life of more than 50 hr at 700°F in essentially oxygen-free systems. New products in this class of hydraulic fluids are constantly being developed so it is not practical to specify property limits here. However, the developmental hydraulic fluids generally have properties superior to the specification fluids. This result is, of course, the objective of the research efforts.

4-5.2 NONPETROLEUM BASE HYDRAULIC FLUIDS

4-5.2.1 Phosphate Esters

The nonspecification and commercial phosphate ester hydraulic fluids have chemical and physical properties which are generally similar, or somewhat superior, to the specification phosphate ester fluids discussed in par. 4-4.1. Three groups of materials, called tertiary phosphate esters, are products whose physical properties vary with type of ester and molecular weight.

One group, the trialkyl phosphates, range from water soluble liquids to water immiscible liquids, or low melting solids, with increasing molecular weight.

A second group, alkyl aryl phosphates are intermediate range phosphates that vary from mobile liquids to low-melting-point solids depending upon chemical structure. These liquids have a typical viscosity range of 1.5 to 10 cSt at 210°F and viscosity indices up to 160. The recommended maximum operating temperature of this class of phosphate esters, which is probably the most widely used material for fire-resistant hydraulic fluids, is as high as 350°F. The phosphate esters have flash points which range from 200° to 500°F with fire points from 50°F to more than 300°F above the flash points. However, the most indicative property, as a

measure of the flammability of phosphate esters, is the spontaneous or autogenous ignition temperature which ranges from 800°F to more than 1,100°F.

The third group, the triaryl phosphates, are the most viscous of the tertiary phosphate compounds, have a short liquid range, and are essentially water insoluble. This type of phosphate has a maximum recommended bulk operating temperature range between 150° and 200°F which is somewhat lower than the aryl phosphates. Their applications are mostly as compounding ingredients for synthetic hydraulic fluids.

The major advantage of the phosphate esters as a class of hydraulic fluids is their fire resistant properties combined with their ability to lubricate moving parts, especially steel on steel.

Some of the names of commercial liquids of the phosphate ester-type widely used by industry are:

1. *Skydrol 7000 and 500A* (Monsanto Chemical Company)

Both of these hydraulic fluids are fire-resistant phosphate esters containing small amounts of several additives (the 7000 and 500 designations refer to the fluid viscosity in centistokes at -40°F). These fluids were developed for use in transport aircraft hydraulic systems. Skydrol 500A has been adopted as the standard hydraulic fluid by most of the world's airlines.

2. *Pydraul* (Monsanto Chemical Company)

These liquids are a series of fire-resistant phosphate esters and additive-containing hydraulic fluids developed for industrial machinery. Pydraul hydraulic fluids are less expensive than Skydrol and are available in a range of viscosities to fit numerous industrial applications. Pydraul AC, although produced primarily as a fire-resistant lubricant for air compressor systems, may also be used in certain hydraulic systems.

3. *FRYQUEL (Cellulube)* (Stauffer Chemical Company)

These liquids are a group of fire-resistant triaryl phosphate ester hydraulic fluids and/or lubricants available in controlled viscosity ranges. The product or fluid numbers represent the fluid viscosity at 100°F in Saybolt Universal Seconds (SUS). Products available include FRYQUEL 90, 150, 220, 300, 550, and 1,000. Although these liquids function primarily as fire-resistant hydraulic fluids, they also find applications as lubricants where fire resistance is not a requirement.

4. *Houghto-Safe* (E. F. Houghton and Company)

These products are also a series of phosphate ester fire-resistant hydraulic fluids and lubricants which have properties and recommended usage similar to the Cellulube and Pydraul fluids. (The reader is reminded

that "Houghto-Safe" is also the name of a glycol water fluid.)

5. *Other Phosphate Ester Base Hydraulic Fluids and Lubricants*

In addition to these typical commercial products, phosphate ester liquids are compounded with many different materials to produce new liquids for different applications. Some of these liquids are compounds of several types of phosphate esters and additives; others are compounds of phosphate esters and other liquids such as chlorinated silicone liquids. In general, the purpose of these developmental oils is to improve or extend the operating temperature limits and the range of certain characteristics such as lubricity, antiseize, and viscosity index.

4-5.2.2 Halogenated Compounds

4-5.2.2.1 Polysiloxanes (Silanes)

These compounds are silicone-containing materials being investigated for applications as hydraulic fluids. These liquids have molecular structures which contain only silicon-to-carbon bonds and no silicon-oxygen bonds as do other silicones and silicate esters. The molecular organic radical of these fluids may be paraffinic or aromatic hydrocarbons with mixtures of alkyl, aryl, alkaryl, or arylalkyl groups present.

In general, these liquids have poor lubricity and a narrow viscosity range. Some additives have shown promise of improving selected characteristics; some polymers are effective in increasing the viscosity; tricresyl phosphate and sodium petroleum sulfonate both act as antiwear additives, and sodium and potassium amides are effective as antioxidants. Because of superior thermal stability and chemical inertness, the silanes appear to be a promising base stock for hydraulic fluids for use in the temperature range of 0° to more than 700°F. Typical properties of silane fluids are pour point, -25°F; flash point, above 500°F; bulk density, 7.4 lb/gal; and viscosity, 37 cSt at 100°F.

4-5.2.2.2 Hydrocarbons

The halogenated hydrocarbon liquids possess several properties that make them attractive for use as hydraulic fluids. They have outstanding fire resistance, good thermal stability and heat-transfer characteristics, good oxidative stability, and boundary-lubrication activity. However, they do have some deficiencies, i.e.,

poor viscosity-temperature properties and high freezing point.

Some of the commercial hydrocarbon liquids usable as hydraulic fluids and/or lubricating fluids are:

(1) *Aroclor* (Monsanto Chemical Company)

Aroclor fluids are a series of hydrocarbon liquids containing chlorinated biphenyls and cover a wide range of viscosities. These fluids have excellent shear resistance, are thermally and chemically stable, non-corrosive, and provide a high degree of extreme pressure lubricity.

(2) *Kel-F Fluids* (Halocarbon Corporation)

The Kel-F fluids are a series of wide range hydrocarbon hydraulic fluids and oils containing halofluorocarbon oils. These fluids are fire-resistant, chemically and thermally stable, and may be used in mechanisms associated with reactive chemicals. The Kel-F fluids have extreme resistance to breakdown, and excellent flow and load-bearing characteristics. In addition to hydraulic fluid applications, they are also employed as compressor lubricants.

(3) *Fluorolube* (Hooker Chemical Company)

The Fluorolube fluids are a series of hydrocarbon compounded liquids of similar composition, properties, and usage as the Kel-F fluids.

4-5.2.2.3 *Perfluorinated Polymers*

The perfluorinated polymers are stable, high-temperature liquids capable of use in the range of -50° to $+700^{\circ}\text{F}$ that do not form sludge or tar even in the presence of air. These liquids have excellent flow characteristics, outstanding thermal and chemical stability, generally good corrosion characteristics, and are compatible with most metals and seal materials. A typical commercial fluid of this type is Krytox 143 (E. I. du Pont de Nemours and Company). Perfluorinated polymers are corrosive with certain metals above 500°F , and provide little or no protection against rusting of ferrous metals at relatively high humidities.

4-5.2.3 *Polyphenyl Ethers*

This class of liquids has been proposed for use as a high-temperature hydraulic fluid and considerable investigation has been conducted in this direction. Generally, these liquids have good oxidation stability, do not hydrolyze, resist decomposition from radiation,

and are marginal lubricants. Their operating temperature range is room temperature to near $1,000^{\circ}\text{F}$. However, their main deterrent is their deficiency in low-temperature characteristics.

4-5.2.4 *Heterocyclic Compounds*

Several heterocyclic compounds have been investigated for applications as synthetic hydraulic fluids and lubricants. The most promising are those compounds containing nitrogen, which show thermal stability above 800°F to around $1,200^{\circ}\text{F}$. Other heterocyclic compounds are less stable. At the present time, no commercial fluids of this class are available.

4-5.2.5 *Phosphonitrilates*

These liquids are being investigated as intermediate temperature range hydraulic fluids and also as lubricants. Generally, they are stable to hydrolysis and resist thermal polymerization up to 750°F . These liquids are still classed as research items and no commercial fluids are available.

4-5.2.6 *Liquid Metals*

Liquid metals have some possible usage as hydraulic fluids for special applications at very high temperatures (to $1,500^{\circ}\text{F}$). The liquid metal which has been investigated most, identified as NAK-77, is a mixture of sodium and potassium. This liquid is silvery in appearance (similar to mercury), and highly reactive with oxygen so that it must be used in closed oxygen-free systems. The mixture melts at about 10°F , atomizes in air at room temperature, and ignites spontaneously in air at 239°F . If water is present, NAK-77 reacts violently, releasing hydrogen and heat sufficient to ignite both the hydrogen and the NAK-77 if any oxygen is present. Surface tension is about twice that of water and its specific gravity is slightly less than water. Viscosity is about 0.50 cSt at 115°F and the friction coefficient is high, about 10 times that of light oil.

Handling and usage of liquid metals are difficult since the hydraulic system must be hermetically sealed and contain an inert gas. If NAK-77 burns, it is nonexplosive unless water is present, but the fumes are toxic.

In addition to NAK-77, other liquid metals have been investigated experimentally but they generally have higher melting points and similar hazardous operating characteristics so that liquid metals seem to offer only limited usage for very special applications.

4-6 HYDRAULIC FLUID AND LUBRICANT SPECIFICATIONS

The following pages contain information on the specifications for hydraulic fluids and lubricants mentioned in preceding paragraphs. For each liquid, data presented are: (a) a Specification Summary Sheet; and (b) Specification Property Requirements Sheet. The specifications are presented in the following order:

1. *Petroleum Base Liquids:*

VV-L-800
MIL-L-2104B
MIL-H-5606B
MIL-H-6083C
MIS-10137
MIS-10150
MIL-L-10295A
MIL-H-13866B(MR)
MIL-H-13919B
MIL-F-17111(NORD)
MIL-L-17331F(SHIPS), Amendment 1
MIL-L-17672B
MIL-L-21260A
MIL-F-25598(USAF)
MIL-H-27601A(USAF)
MIL-L-45199A
MIL-H-46001A
MIL-L-46002(ORD)
MIL-L-46004(ORD)
MIL-H-81019(WEP)

2. *Phosphate Ester Liquids:* MIL-H-19457B (SHIPS)

3. *Silicate Ester Liquids:* MIL-H-8446B

4. *Organic Acid Ester Liquids:* MIL-6085A; MIL-L-7808G; MIL-L-23699A

5. *Polysiloxane Liquids:* MIL-S-81087A(ASG); VV-D-001078 (GSA-FSS)

6. *Glycol Liquids:* MIL-H-5559A(WEPS)

7. *Castor Oils Liquids:* MIL-P-46046A(MR); JAN-F-461

8. *Polyoxyalkylene Glycol Liquids:* MIL-H-13910B; VV-B-680a

9. *Water Glycol Liquids:* MIL-H-22072A(WP)

The code assigned to the abbreviations for military activities listed as the custodians of a specification is:

Army-MR: U.S. Army Materials Research Agency
Watertown, Massachusetts 02172

Army-GL: U.S. Army Natick Laboratories
Natick, Massachusetts 07162

Navy-SH: Naval Ship Engineering Center
Washington, D.C. 20360

Navy-WP: Naval Air Systems Command (AS)
Washington, D.C. 20360

Navy-SA: Naval Supply Systems
Command Headquarters
Washington, D.C. 20360

Navy-YD: Naval Facilities Engineering
Headquarters Command
Washington, D.C. 20360

Air Force-11: Systems Engineering Group
(AFSC, SEP)
Wright-Patterson AFB, Ohio 45433

Air Force-67: Middletown Air Material Area
(MAAMA, MANSS)
Olmsted AFB, Pennsylvania 17057

VV-L-800: LUBRICATING OIL, GENERAL PURPOSE, PRESERVATIVE (WATER-DISPLACING, LOW TEMPERATURE)

(NATO Symbol: 0-190)

a. *General characteristics:* This specification covers a general purpose, water-displacing, lubricating oil for low-temperature applications. It has a pour point of -70°F or lower and a viscosity of 7,000 cSt at -40°F .

b. *Usable temperatures:* The operating temperature range is not specified.

c. *Chemical composition:* This liquid is a petroleum base oil containing additives necessary to meet specification requirements. Principal requirements are for corrosion, oxidation and water displacing properties.

d. *Uses:* This liquid is a lubricating oil for protection against corrosion of small arms, automatic weapons, fuze mechanisms, general squirt-can applications and whenever a general purpose, water-displacing, low temperature, lubricating oil is required.

e. *Limitations:* This liquid loses its Newtonian properties at temperatures below -40°F , should not be used on aircraft equipment such as guns when operation at -65°F is required. Very low-temperature applications should be established by tests.

f. *Custodian:* Army-MR

MIL-L-2104B: LUBRICATING OIL, INTERNAL COMBUSTION ENGINE (HEAVY DUTY)

(NATO Symbol: None)

a. *General characteristics:* This specification covers a multi-grade, detergent-type, petroleum base oil which may contain additives to meet specification requirements.

VV-L-800: LUBRICATING OIL, GENERAL PURPOSE, PRESERVATIVE (WATER-DISPLACING, LOW TEMPERATURE)	
PROPERTIES	VALUES
Color:	No. 7 (Max) (ASTM)
Specific Gravity:	NR
Pour Point, °F; (Max):	-70
Flash Point, °F; (Min):	275
Viscosity, cSt: -65°F (Max)	60,000
-40°F (Max)	7,000
100°F (Min)	12
Neutralization No.: mg KOH/g (Max)	Report
Additives: Antiwear (tricresyl phosphate); % wt	As Req'd and Approved
Oxid. Inhibitors, % wt	As Req'd and Approved
Pour Point Depressant, % wt	As Req'd and Approved
Viscosity Improvers % wt	As Req'd and Approved
Others	As Req'd and Approved
Precipitation No..	0.05
Water Content: % (Max)	--
Corr. and Oxid. Stability: Steel	±0.20
168 hr at 250°F Aluminum Alloy	±0.20
Max wt Chg, mg/cm ² Magnesium Alloy	±0.20
Cad.-Plate	±0.20
Copper	±0.20
Pitting, Etch and Corr. at 20X	None
% Vis Chg at 100°F	-5 to +20
Neutral. No. Increase (Max)	0.20
Insoluble Mat'l or Gumming; % wt	None
Copper Corr.: 72 hr at 212°F	No. 3 (ASTM)
Low Temperature Stability: 72 hr at -65°F	No Solids, nongel
Rubber Swell: Type "L", Vol Chg; %	--
Solid Particle Content: 5-15 Microns	--
(Max Parts/100 ml) 16-25 Microns	--
26-50 Microns	--
51-100 Microns	--
Over 100 Microns	--
Evaporation: 4 hr at 150°F	--
Corrosivity: brass-steel, 10 days, 75°F, 50% R.H.	No Corrosion
Recommended Temperature Range, °F:	> -40
NATO Symbol:	0-190
Storage Stability:	--
Compatibility:	--
Water Stability: 1 hr at 77°F, 50% R.H.	No Corrosion
Humidity Cabinet: 8 days, 95-100% R.H.	Three 1.0 mm dots
Machine Gun Test: -75°F, 25 Rounds	No Stoppage
Notes: NR, no requirements. --, no information.	
Use: General purpose water displacing lub at low temperature, corrosion protection for small arms and automatic weapons.	

MIL-L-2104B: LUBRICATING OIL, INTERNAL COMBUSTION ENGINE (HEAVY DUTY)	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR
Pour Point, °F (Max): Grade 10	-20
Grade 30	0
Grade 50	+15
Stable Pour Point, °F (Max): Grade 10 (only)	-20
Flash Point, °F (Min): Grade 10	360
Grade 30	390
Grade 50	400
Viscosity, cSt: 0°F; Grade 10 (Max)	2,614
0°F; Grade 30 (Max)	43,570
0°F; Grade 50 (Max)	NR
210°F; Grade 10	5.44- 7.29
210°F; Grade 30	9.65-12.98
210°F; Grade 50	16.83-22.7
Additives:	Allowed (No rerefined)
Oxid. Characteristics: (ferrous and nonferrous engine parts)	No Corrosion
Low Temperature Deposit: 180 hr low temp cycle	Slight Corrosion
Ring Stick: 120 hr engine test	Nonstick, min wear
Light-load deposit accumulation: 120 hr engine test	Minimize Deposit
Foaming: 75°F, after 5.0 min blowing, ml (Max)	No limit
75°F, after 10.0 min settling, ml (Max)	300
200°F after 5.0 min blowing, ml (Max)	No limit
200°F after 10.0 min settling, ml (Max)	25
Repeat 75°F Test	Same as init. 75°F Test
Oil Additive Stability:	No additive instability
Storage Stability:	Remain Homogeneous
Compatibility:	All oils to Spec
Recommended Temperature Range, °F:	Above -10
NATO Symbol:	None
Water Content:	--
Notes: NR, no requirements. --, no information.	
Use: Heavy duty engine oil for reciprocating engines, etc.	

b. *Usable temperatures:* The operating temperature range is not specified, but use above -10°F is recommended.

c. *Chemical composition:* This liquid is a petroleum base oil which may contain antifoam and pour point depressant additives, as well as corrosion and oxidation inhibitors to meet specification requirements. It shall not contain any re-refined components.

d. *Uses:* This liquid is for crankcase lubrication of reciprocating internal combustion engines of both spark-ignition and combustion-ignition types when ambient temperatures are above -10°F .

e. *Limitations:* This liquid is not recommended for gear box applications without prior performance evaluation. For highly supercharged compression-ignition engines operating at output levels of 150 psi brake mean effective pressure or above, it may be necessary to decrease oil drain periods or change to oils supplied under MIL-L-45199A and specifically intended for this service. This liquid shall be compatible with other oils qualified to this specification and shall have good storage life when stored in closed containers at normal temperatures.

f. *Custodians:* Army-MR
Navy-SH
Air Force-11

MIL-H-5606B: HYDRAULIC FLUID, PETROLEUM BASE; AIRCRAFT, MISSILE, AND ORDNANCE

(NATO Symbol: H-515)

a. *General characteristics:* This specification covers a petroleum base hydraulic fluid for low temperature applications. It is dyed red for identification purposes.

b. *Usable temperatures:* The recommended operating temperature ranges are -65° to 160°F in open systems and -65° to 275°F in closed systems.

c. *Chemical composition:* This liquid is a petroleum base oil with the following additives: viscosity index improver, oxidation inhibitor, and TCP antiwear agent. The finished liquid must not contain any pour point depressants.

d. *Uses:* The primary uses for this liquid include aircraft hydraulic system, automatic pilots, shock struts, brakes and flap control mechanisms. It is also used in missile hydraulic servo-controlled systems and ordnance hydraulic systems using synthetic sealing materials.

e. *Limitations:* Since this material has a rather high rate of evaporation, it should not be used as a general purpose high temperature lubricant or in

“open” hydraulic system unless the reservoir is filled frequently. It is most effective in “closed-system” hydraulic units. It is not interchangeable with any other types of hydraulic fluid.

f. *Custodians:* Army-MR
Navy-WP
Air Force-11

MIL-H-6083C: HYDRAULIC FLUIDS, PETROLEUM BASE, FOR PRESERVATION AND TESTING

(NATO Symbol: C-635)

a. *General characteristics:* This liquid is a petroleum base corrosion preservative for hydraulic equipment. The finished product shall have no deleterious effect on pressure-seal packing used on aircraft hydraulic systems and shock struts.

b. *Usable temperatures:* The operating temperature range is -65° to $+160^{\circ}\text{F}$.

c. *Chemical composition:* The finished liquid shall be a petroleum base oil with additives to provide corrosion protection and to improve the viscosity/temperature characteristics and resistance to oxidation. No pour point depressant additive is allowed.

d. *Uses:* This fluid is intended as a preservative oil in aircraft and ordnance hydraulic systems during shipment and storage, and also as a testing and flushing liquid for hydraulic system components. It is not intended as an operational hydraulic fluid, but may be used for limited operational use.

e. *Limitations:* Not recommended for high temperature use or for heavy duty requirements. This liquid is not interchangeable with Hydraulic Fluid, Castor Oil Base, Specification MIL-H-7644(USAF) or Hydraulic Fluid, Nonpetroleum Base, Automotive, Specification VV-B-680a.

f. *Custodians:* Army-MR
Navy-SA
Air Force-11

MIS-10137: HYDRAULIC FLUID, PETROLEUM BASE, INTERMEDIATE VISCOSITY

(NATO Symbol: None)

a. *General characteristics:* This hydraulic fluid is a petroleum base liquid containing additives for moderate temperature ranges. It is dyed dark green or dark blue for identification purposes.

b. *Usable temperatures:* The operating temperature range is not specified.

c. *Chemical composition:* This liquid is a refined petroleum base liquid with additive materials to improve oxidation resistance and viscosity-temperature

MIL-H-5606B: HYDRAULIC FLUID, PETROLEUM BASE, AIRCRAFT, MISSILE AND ORDNANCE	
PROPERTIES	VALUES
Color:	Red
Pour Point, °F (Max):	-75
Flash Point, °F (Min):	200
Viscosity, cSt:	3,000
-65°F (Max)	500
-40°F (Max)	10
130°F (Min)	0.50
Additives: Antiwear; % wt	≤ 2.00
Oxidation Inhibitors, % wt	NR
Corrosion Inhibitors, % wt	≤ 20.00
Viscosity Improvers, % wt	No Pour Point Dep.
Others	0.20
Neutralization No.: mg KOH/g (Max)	NR
Precipitation No.: (Max)	Oily, nontacky
Evaporation: 4 hr at 150°F	±0.20
Corr. and Oxid. Stability: Steel	±0.20
168 hr at 250°F,	±0.20
Aluminum Alloy	±0.20
Max wt Chg,	±0.20
Mg/cm ²	±0.20
Cad.-Plate	±0.60
Copper	None
Pitting, Etch. or Corr. at 20X	-5 to +20
Visc Chg at 130°F, %	+0.20
Neutral. No. Chg (Max)	2,500
Solid Particle Content: 5-15 Microns	1,000
(Max Part/100 ml) 16-25 Microns	250
26-50 Microns	25
51-100 Microns	None
Over 100 Microns	No. 2 (ASTM)
Copper Strip Corr.: 72 hr at 250°F (Max)	No Solids, nongel
Low Temp Stability: 72 hr at -65°F	19-28
Rubber Swell: Type "L" Vol Chg, %	65
Foaming: After 5.0 min blowing, ml (Max)	None
(at 75°F) After 10.0 min settling, ml (Max)	12.0
Storage Stability: 75°F, months (Min)	100 ppm
Water Content: (Max)	-65/160 (275)
Recommended Temp. Range, °F: Air (closed)	NR
Specific Gravity:	≤ -15%
Shear Stability: Visc Chg; cSt/130°F (Max)	≤ Ref. Fluid
(30 min Sonic Oscil.) Visc Chg; cSt/-40°F (Max)	≤ 0.20
Neutral. No. Chg (Max)	H-515/none
NATO Symbol/Interchangeable Hyd. Fluid:	NR
Corr. Prot. (bare steel): 100 hr at 120°F, 100% R.H.	
Notes: NR, no requirements.	
RT, room temperature.	
Use: Auto. pilots, shock absorbers, brakes, flap controls, missile servo, and other systems using synthetic seals.	

MIL-H-6083C: HYDRAULIC FLUID, PETROLEUM BASE, FOR PRESERVATION AND TESTING

PROPERTIES	VALUES
Color:	Red (Clear)
Pour Point, °F (Max):	-75
Flash Point, °F (Min):	200
Viscosity, cSt: -65°F (Max)	3500
-40°F (Max)	800
130°F (Min)	10
Additives: Antiwear; % wt	0.50
Oxidation Inhibitors, % wt	≤ 2.00
Corrosion Inhibitors, % wt	Allowed
Viscosity Improvers, % wt	10.0
Others	No Pour Point Dep.
Neutralization No.: mg KOH/g (Max)	0.20
Precipitation No.: (Max)	0
Evaporation: 4 hr at 150°F	NR
Corr. and Oxid. Stability: Steel	±0.20
168 hr at 250°F, Aluminum Alloy	±0.20
Max wt Chg, Magnesium	±0.20
mg/cm ² , Cad.-Plate	±0.20
Copper	±0.60
Pitting, Etch. or Corr. at 20X	None
Visc. Chg at 130°F, %	-50 to +20
Neutral. No. Chg (Max)	0.30
Solid Particle Content: 5-15 Microns	2,500
(Max Part/100 ml) 16-25 Microns	1,000
26-50 Microns	250
51-100 Microns	25
Over 100 Microns	5
Copper Strip Corr.: 72 hr at 250°F (Max)	No. 3 (ASTM)
Low Temp Stability: 72 hr at -65°F	No Solids, nongel
Rubber Swell: Type "L" Vol Chg, %	19-26.5
Foaming: (75°F) After 5.0 min blowing, ml (Max)	65
After 10.0 min settling, ml (Max)	Complete collapse
Storage Stability: 75°F, months (Min)	NR
Water Content: % (Max)	0.05
Recommended Temp Range, °F: Air	-65/160
Specific Gravity:	NR
Shear Stability: Visc Chg; cSt/130°F (Max)	$\left\{ \begin{array}{l} 5,000 \text{ pump cycle; Test} \\ \leq \text{Ref. fluid, MIL-F-5602} \\ +0.30 \end{array} \right\}$
(30 min Sonic Oscil.) Visc Chg; cSt/-40°F (Max)	
Neutral. No. Chg (Max)	
NATO Symbol/Interchangeable Hyd. Fluid:	C-635/See Note
Corr. Prot. (bare steel): 100 hr at 120°F, 100% R.H.	Trace

Notes: NR, no requirements.

Not interchangeable with castor oil or nonpetroleum base oils.

Use: Preservative oil for ord. and aircraft systems, test or flush.

MIS-10137: HYDRAULIC FLUID, PETROLEUM BASE, INTERMEDIATE VISCOSITY	
PROPERTIES	VALUES
Color:	Blue/Green
Specific Gravity:	NR
Pour Point, °F (Max):	-75
Flash Point, °F (Min):	200
Viscosity, cSt: 0°F	50 ± 5.0
100°F	7.5 ± 0.5
Neutralization No.: mg KOH/g (Max)	0.20
Additives: % wt; Antiwear (tricresyl phosphate)	0.5 ± 0.1
Oxidation Inhibitor	≤ 2.0
Viscosity Improvers	≤ 10.0
Pour Point Depressant	None
Others	Approval Req'd
Corr. and Oxid. Stability: Steel	±0.20
168 hr at 250°F Aluminum Alloy	±0.20
Max wt Chg, Magnesium Alloy	±0.20
mg/cm ² Cad.-Plate	±0.20
Copper	±0.60
Pitting, Etch or Corr. at 20X	None
% Visc Chg at 130°F	-5 to +20
Increase in neutral No. (Max)	0.20
Insoluble Mat'l or Gumming	None
Low Temperature Stability: 72 hr at -65°F	No Solid, nongel
Rubber Swell: Type "L", % Vol Chg	19-28
Evaporation: 4 hr at 150°F	Oily, nontacky
Copper Strip Corr.: 72 hr at 250°F (Max)	No. 2 (ASTM)
Solid Particle Content: 5-15 Microns	2,500
(Max Parts/100 ml) 16-25 Microns	1,000
15 min Max filter	
time 26-50 Microns	250
51-100 Microns	25
Over 100 Microns	None
Weight of Residue: mg (Max)	0.30
Forming: (75°F) after 5.0 min blowing, ml (Max)	65
after 10.0 min settling ml (Max)	None
Water Content: % (Max)	0.015
Storage Stability: (70°-120°F) month (Min)	12
NATO Symbol:	None
Recommended Temperature Range, °F:	Intermediate
Compatibility:	None Recommended
Notes: NR. no requirements.	
Use: Guided missile (NIKE) hydraulic systems, moderate temperatures.	

characteristics, and tricresyl phosphate for antiwear properties. The liquid may also be prepared by blending equal quantities of fluids on the qualified products list of MIL-H-5606 and MIL-H-46004.

d. *Uses:* This hydraulic fluid is for guided missile hydraulic systems such as the NIKE HERCULES Missile System at intermediate temperatures.

e. *Limitations:* This liquid shall contain no pour point depressants, admixtures of resins, rubber, soaps, gums, fatty oils, oxidized hydrocarbons or other additives unless specifically approved. It has a storage life of 12 months under normal conditions (-70° to $+120^{\circ}\text{F}$).

f. *Custodian:* U.S. Army Missile Command
Redstone Arsenal, Alabama 35809

**MIS-10150: HYDRAULIC FLUID, PETROLEUM
BASE, LOW TEMPERATURE, COR-
ROSION PREVENTING**

(NATO Symbol: None)

a. *General characteristics:* This liquid is a petroleum base hydraulic fluid containing additives for use in aircraft, missile, and ordnance hydraulic systems in the low temperature range. It has a pour point of -90°F and a viscosity of 800 cSt at -65°F .

b. *Usable temperatures:* The operating temperature range is not specified, but the liquid is generally for very low temperature applications (to -90°F) and moderate high temperatures (less than $+200^{\circ}\text{F}$).

c. *Chemical composition:* The finished liquid is a clear and transparent petroleum base fluid with polymeric additives to improve viscosity-temperature characteristics, and other additives to inhibit oxidation and corrosion and to improve antiwear properties.

d. *Uses:* This hydraulic fluid is intended for use in automatic pilots, shock absorbers, brakes, flap-control mechanisms, missile hydraulic servo-controlled systems, and other hydraulic systems using synthetic sealing materials.

e. *Limitations:* This hydraulic fluid is not for high temperature applications, and is not interchangeable with any other hydraulic fluid except as specified in equipment Technical Manuals. It has a normal storage life of 12 months.

f. *Custodian:* U.S. Army Missile Command
Redstone Arsenal, Alabama 35809
(ERR MI-56001)

**MIL-L-10295A: LUBRICATING OIL, INTERNAL
COMBUSTION ENGINE, SUB-ZERO**

(NATO Symbol: None; Product Symbol: OES)

a. *General characteristics:* This specification covers a light duty, low viscosity oil with suitable additives to meet specification requirements for low ambient temperatures.

b. *Usable temperatures:* This liquid is intended for use at ambient temperatures from -65° to 0°F .

c. *Chemical composition:* This liquid is a petroleum base oil, or a synthetically prepared product, or combination thereof, with suitable additives to meet the requirements of this specification including foaming, oxidation, ring stick and wear tests, as well as viscosity range, flash, pour point, etc.

d. *Uses:* This liquid is used for crankcase lubrication of reciprocating internal combustion engines at very low ambient temperatures, and other applications where a light duty nonoxidizing and nondeposit-forming oil is required.

e. *Limitations:* This liquid is not for high temperature or heavy duty applications. This liquid is to be compatible with all engine oils previously qualified to this specification. It has good storage life when stored in closed containers at normal temperatures.

f. *Custodians:* Army-MR
Navy-SH
Air Force-11

**MIL-H-13866B(MR): HYDRAULIC FLUID, PETRO-
LEUM BASE, ARTILLERY
RECOIL, SPECIAL**

(NATO Symbol: None)

a. *General characteristics:* This hydraulic fluid is one grade of special recoil hydraulic fluid for shock load mechanisms. The liquid is clear and transparent and is dyed green for identification purposes.

b. *Usable temperatures:* The usable temperature range is not specified, but is generally limited to between -30° and $+200^{\circ}\text{F}$.

c. *Chemical composition:* The finished liquid base is a refined mineral oil—free from resin, soap, unrefined oils, and injurious ingredients which may affect the proper function of the fluid. Viscosity index improvers, oxidation inhibitors, and other additives—within defined limits—may be added if needed to meet specification requirements.

d. *Uses:* This hydraulic fluid is primarily for ordnance equipment such as hydrosprings and hydro-pneumatic artillery recoil mechanisms. It may also be used in other fluid or force damping mechanisms.

e. *Limitations:* This hydraulic fluid is not suitable for extreme temperatures; the fluid, and any of its components, must not be subjected to temperatures above 300°F during blending or subsequent operation.

f. *Custodian:* Army-MR

MIS-10150: HYDRAULIC FLUID, PETROLEUM BASE, LOW TEMPERATURE, CORROSION PREVENTING	
PROPERTIES	VALUES
Color:	Clear and Transparent
Specific Gravity:	NR
Pour Point, °F (Max):	-90
Flash Point, °F (Min):	200
Viscosity, cSt:	--
-90°F (Max)	--
-80°F (Max).	800
-65°F (Max)	200
-40°F (Max)	5
130°F (Min)	2.5
210°F (Min)	0.20
Neutralization No.: mg KOH/g (Max)	0.5 ± 0.1
Additives: % wt; Antiwear (tricresyl phosphate)	≤ 2.0
Oxidation Inhibitor	As Req'd and Approved
Corrosion Inhibitor	≤ 10.0
Viscosity Improver	±0.20
Corr. and Oxid. Stability: Steel	±0.20
168 hr at 250°F Aluminum Alloy	±0.20
Max wt Chg, Magnesium Alloy	±0.20
mg/cm ² Cad.-Plate	±0.20
Copper	±0.60
% Visc Chg at 130°F	-5 to +20
Pitting, Etch or Corr. at 20X	None
Increase in Neutral. No. (Max)	0.20
Insoluble Mat'l or Gummy	None
Low Temperature Stability: 72 hr at -65°F	No Solids, nongel
Shear Stability: Viscosity Chg at 130°F (Max)	< Ref. Fluid
(30 min sonic oscil.) Viscosity Chg at -40°F (Max)	< Ref. Fluid
Neutral. No. Chg (Max)	≤ 0.20
Evaporation: 4 hr at 150°F	Oily, nontacky
Copper Strip. Corr.: 72 hr at 250°F (Max)	No. 2 (ASTM)
Solid Particle Content: 5-15 Micron	2,500
(Max Parts/100 ml) 16-25 Micron	1,000
26-50 Micron	250
51-100 Micron	25
Over 100 Micron	None
Foaming: (75°F) after 5.0 min blowing; ml (Max)	65
after 10.0 min settling; ml (Max)	None
Rubber Swell: Type "I", Vol Chg, %	19-28
Water Content: % (Max)	0.08
Storage Stability: (-80° to 120°F) Months (Min)	12
Recommended Temperature Range, °F:	Low Temperature
Compatibility Hyd Fluids: (Emergency Only)	None
NATO Symbol:	None
Corr. Inhib. (humidity): 20 hr at 72°F (bare steel)	No Corrosion
Corrosivity (brass and steel): 10 days at 80°F	No Corrosion
Wear (Steel): Shell 4-ball; (2 hr, 167°F,	
40 kg 1,200 rpm) Scar Dia	< 1.0 mm
Notes: NR, no requirements.	
--, no information.	
Use: Auto-pilots, shock absorbers, brakes, flap-control mech., missile hyd. servo-control and other systems using synthetic seals.	

MIL-L-10295A: LUBRICATING OIL, INTERNAL COMBUSTION ENGINE, SUB-ZERO	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR - Report
Pour Point, °F (Max):	-65
Stable Pour Point, °F (Max):	-65
Flash Point, °F (Min):	290
Viscosity, cSt: -40°F (Min)	5.75
-210°F (Max)	8,500
Additives:	Allowed
Effect of Additives: Increase in foam	None
Homogeneity Range, °F	-65 to +250
Storage Stability	No Separation
Oxid. Characteristics: (ferrous and nonferrous engine parts)	No Corrosion
Ring Stick: 120 hr Engine Test	Nonstick, Report mm Wear
Foaming: 75°F, after 5.0 min blowing, ml (Max)	No limit
75°F, after 10.0 min settling, ml (Max)	300
200°F, after 5.0 min blowing, ml (Max)	No limit
200°F, after 10.0 min settling, ml (Max)	25
Repeat 75°F test	Same as init. 75°F Test
Compatibility:	All oils to Spec.
Water Content, %:	None
Suspended Matter, %:	None
Storage Stability:	NR
NAIO Symbol:	None
Recommended Ambient Temperature Range, °F:	-65 to 0
<p>Notes: NR, no requirements.</p> <p>Use: Low temperature lub for crankcase of internal combustion engines. May be synthetic base.</p>	

MIL-H-13866B(MR): HYDRAULIC FLUID, PETROLEUM BASE, ARTILLERY RECOIL, SPECIAL	
PROPERTIES	VALUES
Color:	Green (Clear)
Specific Gravity, 60/60, °F:	15
Pour/Cloud Points, °F (Max):	-50/-40
Flash/Fire Points, °F (Min):	210/220
Viscosity, cSt: -40°F (Max)	--
-30°F (Max)	4,400
100°F (Min)	55
210°F (Min)	15
Additives: Oxidation Inhibitors, % wt	Approval Req'd
Corrosion Inhibitors, % wt	Approval Req'd
Viscosity Improvers, % wt	< 17.5
Others	None
Neutralization No.: mg KOH/g (Max)	0.30
Precipitation No.: (Max)	0.05
Corr. and Oxid. Stability: Steel	-0.20
168 hr at 212°F	Copper
Max wt Cng,	Pitting, Etch or Corr. at 20X
mg/cm ²	Viscosity Chg at 100°F, %
	Neutralization No.
	Precipitation No.
	Insoluble Mat'l or Gumming
Copper Strip Corr.: 3 hr at 212°F	None
Low Temperature Stability: 72 hr at -30°F	NR
Rubber Swell: Type "L", 168 hr at 70°F, % Vol Chg	Nongel, No. Sep.
Dielectric Strength: kV/mm (Min)	≤ 25.0
Shear Stab.: (Pump); 100°F, Cycles to reduce Visc. 25%	15.0
Corr. Prot.; (bare steel): 200 hr at 77°F, 100% R.H.	> Ref. Fluid*
Salt Water Corr.; (bare steel): 20 hr at 77%	NR
Distillation: 10% Evaporation; °F (Min)	NR
50% Evaporation; °F (Min)	NR
Foaming: 75°F, after 5.0 min blowing; ml (Max)	NR
75°F, after 10.0 min settling; ml (Max)	NR
200°F, after 5.0 min blowing; ml (Max)	NR
200°F, after 10.0 min settling; ml (Max)	NR
Recommended Temperature Range, °F:	--
Service Perf.: (Oil Gear M3), Oil Temperature °F (Max)	NR
Water Content:	--
Notes: NR, no requirements.	
--, no information.	
* R.I.A. Ref. Oil No. 1.	
Use: Hydrosprings and hydropneumatic artillery recoil mechanisms.	

**MIL-H-13919B: HYDRAULIC FLUID, PETROLEUM
BASE, FIRE-CONTROL**

(NATO Symbol: None)

a. *General characteristics:* This hydraulic fluid is a rust inhibiting, petroleum base liquid, containing additives, for use at ambient temperatures above 0°F. ASTM color is Code No. 5 Max, bright in color and free of haze.

b. *Usable temperatures:* The operating temperature range is not specified.

c. *Chemical composition:* The base liquid is a refined mineral oil, free of unrefined oils and other injurious ingredients which may affect the proper function of the liquid. The finished liquid contains suitable rust-inhibiting and other approved additives.

d. *Uses:* This liquid is a medium grade rust-inhibiting, ambient temperature, ordnance hydraulic fluid for use in fire control systems, hydraulic variable speed gears, and in other hydraulic mechanisms where recommended.

e. *Limitations:* This hydraulic fluid is not suitable for extreme temperature applications, below 0°F or above 200°F. It is not recommended or intended for use in aircraft.

f. *Custodian:* Army-MR

**MIL-F-17111(NORD): FLUID, POWER TRANS-
MISSION**

(NATO Symbol: H-575)

a. *General characteristics:* This liquid is a petroleum base, power transmission fluid suitable for use in Naval ordnance systems involving mechanical or fibrous type filters or centrifugal purification. It shall be noncorrosive to bearings and hydraulic systems, and shall not cause clogging of oil screens or valves. It has an ASTM color of Code No. 2.

b. *Usable temperatures:* The operating temperature range is not specified.

c. *Chemical composition:* The finished liquid is a petroleum base fluid plus an antiwear agent tricresyl phosphate, and other approved additives which improve the compounded fluid with respect to viscosity-temperature and lubricating properties, resistance to oxidation, and corrosion protection.

d. *Uses:* This liquid is intended for use in connection with the hydraulic transmission of power, particularly in Naval ordnance hydraulic equipment.

e. *Limitations:* Not for high temperature applications since the fluid is flammable.

f. *Custodian:* Air Force-11

**MIL-L-17331F(SHIPS) Amendment 1: LUBRICATING
OIL, STEAM TURBINE
(NONCORROSIVE)**

(NATO Symbol: 0-250; Military Symbol: 2190-TEP)

a. *General characteristics:* This liquid is a petroleum base steam turbine lubricating oil which may or may not contain additives. The liquid is noncorrosive and has a work factor of 0.9 min.

b. *Usable temperatures:* The operating temperature range is not specified, but general usage is between + 20°F and 190°F with short duration elevated temperature use to 250°F.

c. *Chemical composition:* This liquid is a homogeneous blend of virgin petroleum lubricating oil plus required additives to meet requirements of the specification.

d. *Uses:* This liquid is a steam turbine lubricating oil for main turbines and gears, auxiliary turbine installations, certain hydraulic equipment, general mechanical lubrication, and air compressors.

e. *Limitations:* The liquid has limited use as hydraulic fluid and is not for low temperatures (minimum recommended temperature is +20°F). It is compatible with reference oils furnished by the Government and other oils to this specification.

f. *Custodian:* Navy-SH (Project 9150-N029Sh).

**MIL-L-17672B: LUBRICATING OIL, HYDRAULIC
AND LIGHT TURBINE, NONCOR-
ROSIVE**

(NATO Symbol: H-573)

a. *General characteristics:* This specification covers a multiclass mineral base hydraulic oil containing anticorrosion and antioxidation additives:

1. Military Symbol 2075 T-H
2. Military Symbol 2110 T-H
3. Military Symbol 2135 T-H

b. *Usable temperatures:* The operating temperature range is not specified.

c. *Chemical composition:* This liquid is a blend of virgin petroleum base oils and additives to meet requirements of this specification; including oxidation, corrosion, foam and emulsion tests in addition to viscosity range, flash, pour point, etc.

d. *Uses:* This liquid is for steam turbines, hydraulic systems, water turbines, water-wheel type generators, hydraulic-turbine governors, and other applications where a high grade lubricating oil having anticorrosion and antioxidation properties is required.

e. *Limitations:* There are no storage life requirements, but the liquid has good storage properties if

MIL-H-13919B: HYDRAULIC FLUID, PETROLEUM BASE, FIRE CONTROL	
PROPERTIES	VALUES
Color:	No. 5 (ASTM)
Specific Gravity, 60/60, °F:	NR
Pour/Cloud Points, °F (Max):	-50/NR
Flash/Fire Points, °F (Min):	225/NR
Viscosity, cSt: -40°F (Max)	7,500
-30°F (Max)	NR
100°F (Min)	38
210°F (Min)	10
Additives: Oxidation Inhibitors, % wt	Approval Req'd
Corrosion Inhibitors, % wt	Approval Req'd
Viscosity Improvers, % wt	Approval Req'd
Others	None
Neutralization No.: mg KOH/g (Max)	NR
Precipitation No.: (Max)	0.05
Corr. and Oxid. Stability: Steel	-0.20
168 hr at 212°F Copper	-0.20
Max wt Chg, Pitting, Etch or Corr. at 20X	Slight Etch
mg/cm ² Viscosity Chg at 100°F, %	-5 to +20
Neutralization No.	+0.50
Precipitation No.	≤ 0.05
Insoluble Mat'l or Gumming	None
Copper Strip Corr.: 3 hr at 212°F	No Etch or Pit
Low Temperature Stability: 72 hr at -30°F	Nongel, No Sep.
Rubber Swell: Type "L", 168 hr at 70°F, % Vol Chg	≤ 25.0
Dielectric Strength: kV/mm (Min)	NR
Shear Stab.: (Pump); 100°F, Cycles to reduce Visc. 25%	> Ref. Fluid*
Corr. Prot.; (bare steel): 200 hr at 77°F, 100% R.H.	Slight Trace
Salt Water Corr.; (bare steel); 20 hr at 77%	Slight Trace
Distillation: 10% Evaporation; °F (Min)	490
50% Evaporation; °F (Min)	575
Foaming: 75°F, after 5.0 min blowing; ml (Max)	No limit
75°F, after 10.0 min settling; ml (Max)	≤ 100
200°F, after 5.0 min blowing ml (Max)	No limit
200°F, after 10.0 min settling, ml (Max)	25
Recommended Temperature Range, °F:	Ambient > 0
Service Perf.: (Oil Gear M3), Oil Temperature °F (Max)	≤ 205
Water Content:	None
Notes: NR, no requirements.	
* R.I.A. Ref. Oil No. 1.	
Use: Fire-control hydraulic variable speed gears and other mechanisms. Rust inhibiting.	
Not for aircraft.	

MIL-F-17111 (NORD): FLUID, POWER TRANSMISSION	
PROPERTIES	VALUES
Color:	No. 2 (ASTM)
Specific Gravity:	NR
Pour Point, °F, (Max):	-40
Flash/Fire Points, °F (Min):	220/235
Viscosity, cSt: -25°F (Max)	600
0°F (Max)	215
100°F (Min)	27
210°F (Min)	10
Additives: Antiwear; % wt	Approval Req'd
Oxidation Inhibitor, % wt	Approval Req'd
Corrosion Inhibitor, % wt	Approval Req'd
Viscosity Improver, % wt	Approval Req'd
Tricresyl Phosphate, % wt	1.0 ± 0.1
Neutralization No.: mg KOH/g (Max)	0.3
Precipitation No.:	0.05
Water Content: % (Max)	None
Low Temperature Stability: 72 hr at -35°F	No Solids, nongel
Rust Prevention: (bare steel), 24 hr at 140°F	No Visual Evidence
Corr. and Oxid. Stability: copper wt loss; mg/cm ²	≤ 0.20
336 hr at 220°F % Visc Chg; 210°F	0 to +25
Fluid and water % Visc Chg; 0°F	0 to +25
Neutralization No. (Max)	0.50
Oil-Insoluble Residue; % wt (Max)	0.50
Color; (ASTM) (Max)	No. 5
Copper Wire Oxid.: % Visc Chg; 210°F	0 to +15
72 hr at 200°F % Visc Chg; 0°F	0 to +15
Fluid and Water Neutralization No. (Max)	≤ 0.50
Shear Stability: % Visc Chg at 210°F (Max)	-25
5,000 cycle pump Fluid Condition	No Separation or Sludge
100°F and 1,000 psi Neutralization No. (Max)	0.50
Wear-Gear Pump: Wt Loss/Pump Gear, g	0.20 (Max)
(100 hr, 100°F, 1,000 psi) Wt Loss/Bronze Bushing, g	0.04 (Max)
Wt Loss/4 Bronze Bushings, g	0.08 (Max)
Evaporation: 72 hr at 190°F; Visc.; 210°F, cSt	3,000 (Max)
Water Sludging: 24 hr at 100°F; % Visc Chg at 100°F	-2 to +10
NATO Symbol:	H-575
Recommended Temperature Range, °F:	NR
Foaming:	NR
Storage Stability:	NR
Notes: NR, no requirements.	
Use: Fluid for hydraulic transmission of power, particularly in Naval Ord. Hyd. equipment.	

MIL-L-17331F(SHIPS) AMENDMENT 1: LUBRICATING OIL, STEAM TURBINE (NONCORROSIVE)	
PROPERTIES	VALUES
Color:	NR - Record
Specific Gravity:	NR - Record
Pour Point, °F (Max):	20
Flash Point, °F (Max):	350
Viscosity, cSt: 100°F	82-110
210°F (Min)	8.2
Neutralization No.: mg KOH/g (Max)	0.20
Mineral Acidity:	Neutral
Additives:	Allowed (nonchlorine)
Corr. Prot.: (bare steel) salt spray (fog); 48 hr at 95°F	No Corrosion
Copper strip corr: 3 hr at 212°F	Slight Tarnish
Oxid. Test: (1,000 hr at 95°F): Neutralization No. (Min)	2.0
Iron-Copper Cat., Insoluble Sludge, mg (Max)	100
air and water Copper or iron in oil; mg (Max)	100
Work Factor: (Min)	0.9 (No deposit)
Water Content:	None
Ash (sulphated residue):	NR - Record
Carbon Residue:	NR - Record
Compatibility:	Ref. Oils
Homogeneity Temperature Range, °F:	30 to 250
Foaming: 75°F, after 5.0 min blowing, ml (Max)	No limit
75°F, after 10.0 min settling, ml (Max)	300
200°F, after 5.0 min blowing, ml (Max)	No limit
200°F, after 10.0 min settling, ml (Max)	25
Repeat 75°F Test	Same as init. 75°F Test
Emulsion: 130°F, settling time; min (Max)	30
Load Carrying Ability: (Ryder Gear Machine); P.P.I. (Min)	2,200
Wear: (2 hr 175°F, 600 rpm, 15 kg); Scar. Dia mm (Max)	0.45
Contamination: (325 Mesh); mg/gal; (Max)	10.0
6.0 ml fiber/gal (Max)	1.0
NATO Symbol:	0-250
Military Symbol:	2190-TEP
Storage Stability:	--
Recommended Temperature Range, °F:	--
Notes: NR, no requirements.	
--, no information.	
Use: Steam turbine and gears, hyd. equipment, general mechanical lub., and air compressors.	

MIL-L-17672B: LUBRICATING OIL, HYDRAULIC AND LIGHT TURBINE, NONCORROSIVE	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR - Report
Pour Point, °F (Max): MIL-Symbol 2075 T-H	-20
MIL-Symbol 2110 T-H	-10
MIL-Symbol 2135 T-H	0
Flash Point, °F (Min): MIL-Symbol 2075 T-H	315
MIL-Symbol 2110 T-H	325
MIL-Symbol 2135 T-H	340
Viscosity, cSt: 0°F, MIL-Symbol 2075 T-H	1,200 (Max)
0°F, MIL-Symbol 2110 T-H	2,400 (Max)
10°F, MIL-Symbol 2135 T-H	2,800 (Max)
210°F, MIL-Symbol 2075 T-H	4.3-5.3
210°F, MIL-Symbol 2110 T-H	5.3-6.7
210°F, MIL-Symbol 2135 T-H	6.7-7.7
Neutralization No.: mg KOH/g (Max)	0.20
Neutrality, Qualitative:	Neutral
Copper Strip: 3 hr at 212°F (Max)	No. 1 (ASTM)
Rust Preventative: 24 hr at 140°F	No Corrosion
Water Content: % (Max)	None
Ash, Sulfated Residue :% (Max)	NR - Report
Additives:	Allowed
Homogeneity Temperature Range, °F: MIL-Symbol 2075 T-H	-20 to 250
MIL-Symbol 2110 T-H	-10 to 250
MIL-Symbol 2135 T-H	0 to 250
Emulsion: 130°F, 30 min settling, Max Cuff, ml	3.00
Foaming: 75°F, after 5.0 min blowing, ml (Max)	No limit
75°F, after 10.0 min settling, ml (Max)	300
200°F, after 5.0 min blowing, ml (Max)	No limit
200 °F, after 10.0 min settling, ml (Max)	25
Repeat 75°F Test	Same as init. 75°F Test
Oxid. Test: Time to reach Neut. No. 2.0 mg KOH; hr (Max)	1,000
Contamination: (325 Mesh); mg/gal (Max)	10.0
6.0 ml fibers/gal (Max)	1.0
NATO Symbol:	H-573
Storage Stability:	--
Recommended Temperature Range, °F:	--
Compatibility:	Ref. and Spec. oils
Notes: NR, no requirements. --, no information.	
Use: Mineral oil and additives for steam turbines, hyd. systems, water turbines and other systems, anticorrosion and antioxidant additives are required.	

stored in closed containers at normal temperatures. It shall be compatible with other reference oils furnished by the Government. Compatibility is determined by mixing equal portions of specification oil and reference oil, and passing requirements of this specification.

- f. *Custodians:* Army-GL
Navy-SH
Air Force-11

MIL-L-21260A: LUBRICATING OIL, INTERNAL COMBUSTION ENGINE, PRESERVATIVE

(NATO Symbol: None)

a. *General characteristics:* This specification covers three viscosity grade preservative lubricating oils used as lubricants in spark-ignition and compression-ignition types of reciprocating internal combustion engines.

b. *Usable temperatures:* The operating temperature ranges are not specified.

c. *Chemical composition:* The finished oil may be a petroleum base of a synthetically prepared product, or a combination thereof, with or without additives. However, no re-refined components are permitted.

d. *Uses:* The oil is a crankcase oil for diesel or spark-ignition type internal combustion engines. Although intended principally as a static preservative, this oil may be used as an operating lubricant for short periods, and for some hydraulic equipment. It is compatible with other fluids to this specification and MIL-L-2104.

e. *Limitations:* This oil is not for low temperature usage and not generally for gear box applications.

- f. *Custodians:* Army-MR
Navy-SH
Air Force-11

MIL-F-25598(USAF): OIL, HYDRAULIC, MISSILE, PETROLEUM BASE

(NATO Symbol: None)

a. *General characteristics:* This specification covers a low viscosity hydraulic oil for light or medium duty applications at low temperatures. It has a pour point of -90°F and a viscosity of 600 cSt at -65°F. It is dyed purple for identification purposes.

b. *Usable temperatures:* No specified requirement but intended for temperatures -65°F to +200°F.

c. *Chemical composition:* This liquid is a petroleum base oil containing approved additives to meet specification requirements for oxidation, corrosion and wear (tricresyl phosphate, 0.5 percent by weight, antiwear agent). No pour point depressant shall be used.

d. *Uses:* This liquid is used for low temperature hydraulic systems such as missile hydraulic systems, automatic pilots, shock struts and other hydraulic systems using synthetic sealing material.

e. *Limitations:* This liquid is not for high temperature conditions. It is not interchangeable with Hydraulic Fluid, Castor Oil Base, Specification MIL-H-7644 (blue color) nor Hydraulic Fluid, Petroleum Base, Specification MIL-H-5606B.

- f. *Custodian:* Air Force - WADC, WCRTR-1
(Preliminary Spec.: Non-release)
Wright-Patterson Air Force Base,
Ohio 45433

MIL-H-27601A(USAF): HYDRAULIC FLUID, PETROLEUM BASE, HIGH TEMPERATURE, FLIGHT VEHICLE

(NATO Symbol: None)

a. *General characteristics:* This hydraulic fluid is a petroleum or synthetic hydrocarbon base fluid containing specified additives. The finished fluid has good thermal and electrical properties and a viscosity index of 89 (min).

b. *Usable temperatures:* The operating temperature range is -40° to 550°F.

c. *Chemical composition:* This liquid is a petroleum or synthetic hydrocarbon base fluid with specified amounts of hindered bisphenol oxidation inhibitor and tricresyl phosphate antiwear additives.

d. *Uses:* This fluid can be used in high temperature hydraulic systems, principally for flight vehicles.

e. *Limitations:* The fluid is not suitable or recommended for extreme low temperature operation. Also, this fluid is not compatible with any other hydraulic fluids except those meeting this specification.

- f. *Custodian:* Air Force-11

MIL-L-45199A: LUBRICATING OIL, INTERNAL COMBUSTION ENGINE, HIGH OUTPUT DIESEL

(NATO Symbol: None)

a. *General characteristics:* This specification covers a multi-grade heavy duty crankcase engine oil with a pour point as low as -20°F.

b. *Usable temperatures:* The operating temperature range is not specified.

c. *Chemical composition:* This liquid is a petroleum base oil or synthetically prepared product, or

MIL-L-21260A: LUBRICATING OIL, INTERNAL COMBUSTION ENGINE, PRESERVATIVE	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR
Pour Point, °F (Max): Grade 1	-20
Grade 2	0
Grade 3	+15
Stable Pour Point, °F (Max): Grade 1 only	-20
Flash Point, °F (Min): Grade 1	360
Grade 2	390
Grade 3	400
Viscosity, cSt: Grade 1	2,614/5.44-7.29
(Visc, 0°F (Max))/ Grade 2	43,570/9.65-12.98
Visc, 210°F) Grade 3	NR/16.83-22.75
Viscosity Index: Grade 3 only	75
Volatile Matter: (4 hr steam bath); % wt	2.0
Additives:	Allowed
Corr. Prot.: 200 hr, high-humidity; % Corr.	Trace Only
(Bare Steel, 77°F) salt water dip, 20 hr dry; % Corr.	Trace Only
Acid Neut.: 77°F, acid sol. dip, 4 hr in oil; % Corr.	No Corrosion
Oxid. Characteristics: (ferrous and nonferrous engine parts)	Noncorrosive
Compatibility:	MIL-L-2104
Foaming: 75°F, after 5.0 min blowing, ml (Max)	No limit
75°F, after 10.0 min settling, ml (Max)	300
200°F, after 5.0 min blowing, ml (Max)	No limit
200°F, after 10.0 min settling, ml (Max)	25
75°F, Repeat 75°F Test	Same as init. 75° Test
Water Content: %	--
NATO Symbol:	None
Storage Stability:	--
Recommended Temperature Range, °F :	--
Notes: NR, no requirements.	
--, no information.	
Use: Light, medium, and heavy preservative lub and preservative oil for reciprocating internal combustion engines.	

MIL-F-25598(USAF): OIL, HYDRAULIC, MISSILE, PETROLEUM BASE	
PROPERTIES	VALUES
Color:	Purple (Clear and Transparent)
Specific Gravity:	NR
Pour Point, °F (Max):	-90
Flash Point, °F (Min):	200
Viscosity, cSt: -65°F (Max)	600
-50°F (Max)	240
-40°F (Max)	140
0°F (Max)	28
130°F (Min)	2.6
160°F (Min)	2.0
210°F (Min)	1.25
Neutralization No.: mg KOH/g (Max)	0.20
Precipitation No.:	0
Additives; % wt: Antiwear (tricresyl phosphate) (Max)	0.05 ± 0.1
Oxidation Inhibitor (Max)	< 2.0
Corrosion Inhibitor (Max)	As Req'd
Viscosity Improvers (Max)	None
Others	No Pour Point Dep.
Corr. and Oxid. Stability: Steel	± 0.20
168 hr at 250°F Aluminum Alloy	± 0.20
Max wt Chg, mg/cm ² Magnesium Alloy	± 0.20
Cad.-Plate	± 0.20
Copper	± 0.60
Pitting, Etch and Corr. at 20X	None (slight stain)
% Visc Chg at 130°F	-5 to +20
Neutral. No. Increase (Max)	0.20
Insoluble Mat'l or Gumming	None
Low Temperature Stability: 72 hr at -65°F	No solids, nongel
Rubber Swell: Type "L", Vol, %	19 - 26.5
Evaporation: 4 hr at 150°F	Oily, nontacky
Copper Strip. Corr.: 72 hr at 212°F	No Corrosion (slight stain)
Corr. Prot.: Steel, 100 hr, 120°F, 100% R.H.	Trace of Corrosion
Solids: 250 cc, 0.047 mm filter; Max Part Size	30 micron
Water Content: %	0.005
Storage Stability:	NR
Recommended Temperature Range, °F:	--
NATO Symbol:	None
Compatibility:	Not Interchangeable
Notes: NR, no requirements.	
--, no information.	
Use: Missile hyd. systems using synthetic material.	

MIL-H-27601A(USAF): HYDRAULIC FLUID, PETROLEUM BASE, HIGH TEMPERATURE, FLIGHT VEHICLE	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR - Report
Pour Point, °F (Max):	-65
Flash Point, °F (Min):	360
Viscosity, cSt: -65°F	Report
-40°F (Max)	4,000
0°F (Max)	385
210°F (Min)	3.2
550°F (Min)	Report
Viscosity Index: (Min)	89
Neutralization No.: mg KOH/g (Max)	0.20
Additives, % wt: Antiwear (tricresyl phosphate) (Max)	1.0
Oxidation Inhibitors (bis-phenol)	0.45 - 1.0
Others	Approval Req'd
Corr. and Oxid. Stability: Copper	0.60
48 hr at 347°F	Type 350 St. Steel
Max wt Chg,	Type 355 St. Steel
mg/cm ²	Type 440 St. Steel
	Silver
	% Visc. Chg. at 100°F
	Neutralization No. (Max)
	Insoluble Mat'l % wt (Max)
Thermal Stability: M-10 Tool Steel	0.10
6 hr at 700°F,	52100 Steel
20 psig Nitrogen	Naval Bronze
atmosphere,	% Visc Chg at 100°F (Max)
	Neutral. No. (Max)
Rubber Swell (Syn): Viton A or B; 72 hr at 400°F, % Vol.	0.40
Lubricity; (Shell 4-Ball Tester): 1 kg load	+10.0 (Max)
1.0 hr at 600 rpm, 167°F,	10 kg load
52100 Steel Max Scar Dia mm	40 kg load
Solid Particles: Time to filter 100 ml, min (Max)	0.21
(0.45 Micron filter) Max Particle on filter (Micron)	0.30
Compatibility:	0.65
Foaming: 75°F, after 5.0 min blowing, ml (Max)	10.0
75°F, after 3.0 min settling, ml (Max)	100.0
200°F after 5.0 min blowing, ml (Max)	All fluids to this Spec.
200°F after 3.0 min settling, ml (Max)	75
Repeat 75°F Test	None
Water Content: % (Max)	75
Trace Sediment: % Vol (Max)	None
Dielectric Strength: (volt/ml), 68°F; (Min)	Same as init. 75° Test
Specific Heat: (Btu/lb °F) at 200°F (Min)	0.10
Thermal Cond.: (Btu/(ft ²)(hr)(°F)/ft at 400°F (Min)	0.025
Thermal Expansion/°F: at 400°F (Max)	300
Bulk Mod.: (isothermal secant, 0-10 ⁴ psi, 100°F), psi	0.484
Recommended Temperature Range, °F:	0.063
Storage Stability:	0.00060
	> 200,000
	-40 to +550
	NR
Notes: NR, no requirements.	
Use: Hyd. Systems of flight vehicles.	

MIL-L-45199A: LUBRICATING OIL, INTERNAL COMBUSTION ENGINE, HIGH OUTPUT DIESEL	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR - Report
Pour Point, °F (Max): Grade 10	-20
Grade 30	0
Grade 50	NP
Stable Pour Point, °F (Max): Grade 10 (only)	-20
Flash Point, °F (Min): Grade 10	360
Grade 30	390
Grade 50	NP
Viscosity, cSt: 0°F; Grade 10 (Max)	2,614
0°F; Grade 30 (Max)	43,570
0°F; Grade 50 (Max)	NP
210°F; Grade 10	5.44-7.29
210°F; Grade 30	9.65-12.98
210°F; Grade 50	NP
Additives:	Allowed (No rerefined)
Oxid. Characteristics: (ferrous and nonferrous engine parts)	No Corrosion
Low Temperature Deposit: 180 hr low temp cycle	NR
Ring Stick: 120 hr engine test	No Stick, Min. Wear
Light-load deposit accumulation: 120 hr engine test	NR
Foaming: 75°F, after 5.0 min blowing, ml (Max)	No Limit
75°F, after 10.0 min settling, ml (Max)	300
200°F after 5.0 min blowing, ml (Max)	No Limit
200°F after 10.0 min settling, ml (Max)	25
Repeat 75°F Test	Same as init. 75°F Test
Oil Additive Stability:	No Additive Instability
Storage Stability:	--
Compatibility:	All Oils to Spec.
Recommended Temperature Range, °F:	Above -20
NATO Symbol:	None
<p>Notes: NR, no requirements. --, no information. NP, no product.</p> <p>Use: Crankcase lub of high output diesels where temperature is above -20°F. May be synthetic base.</p>	

combination thereof, with additive materials (detergents, dispersants, oxidation inhibitors, etc.) necessary to meet the requirements of this specification. No re-refined components are allowed.

d. *Uses:* This liquid is for crankcase lubrication of high output supercharged and unsupercharged diesel engines under all conditions of service at ambient temperatures above -20°F .

e. *Limitations:* This liquid is not for use at low temperature conditions. It is compatible with all oils qualified to this specification.

f. *Custodians:* Army-MR
Navy-SH
Air Force-67

**MIL-H-46001A: HYDRAULIC FLUID, PETROLEUM
BASE, FOR MACHINE TOOLS,
TYPES I, II, III, AND IV**

(NATO Symbol: None)

a. *General characteristics:* This liquid is a multi-grade refined petroleum hydrocarbon hydraulic fluid containing additives. It has a viscosity range of 30 to 121 cSt at 100°F , and a minimum viscosity index of 80.

b. *Usable temperatures:* The operating temperature range is not specified, but ambient temperatures should be above $+20^{\circ}\text{F}$.

c. *Chemical composition:* The finished liquid shall be a petroleum base fluid containing additives necessary to meet the requirements of this specification—i.e., oxidation, corrosion, foam, flash, etc.

d. *Uses:* This liquid is primarily for use in hydraulic systems of metalworking machine tools. The selection of the particular type of liquid is based on fluid viscosity recommendations of machine tool manufacturers. The finished liquid shall be compatible with other liquids meeting this specification.

e. *Limitations:* This liquid is not suitable for low temperatures, and ambient temperatures should be above $+20^{\circ}\text{F}$.

f. *Custodians:* Army-MR
Navy-SA
Air Force-11

**MIL-L-46002(ORD): LUBRICATING OIL, CON-
TACT AND VOLATILE, COR-
ROSION INHIBITED**

(NATO Symbol: None)

a. *General characteristics:* This oil is a dual grade volatile corrosion inhibited lubricating oil for preservation of material in enclosed systems. Light and medium viscosity oils are available with pour points of -50°F and -10°F .

b. *Usable temperatures:* The operating temperature range is not specified, but the oil or oil-water vapors shall be capable of protecting parts from corrosion throughout a temperature range of $+40^{\circ}$ to $+130^{\circ}\text{F}$.

c. *Chemical composition:* This oil is a volatile corrosion inhibited, petroleum base oil containing additives necessary to meet specification requirements. The oil shall contain no ingredients injurious to personnel using reasonable safety precautions and must be free from disagreeable or offensive odors.

d. *Uses:* This oil is intended for use in the preservation of enclosed systems where the volatile components will provide protection above the oil level. It is also effective as a contact preservative.

e. *Limitations:* The oil is not intended for use as an operational preservative oil and should not be used in applications where magnesium, cadmium-plated or rubber components are present. Generally, it should not be mixed with other oils to same specification due to wide product tolerances.

f. *Custodian:* Army-MR

**MIL-H-46004(ORD): HYDRAULIC FLUID, PETRO-
LEUM BASE, MISSILE**

(NATO Symbol: None)

a. *General characteristics:* This specification covers a low viscosity liquid containing approved additives for low temperature missile applications. It has a viscosity of 300 cSt at -65°F and a pour point of -75°F . The liquid is dyed yellow for identification purposes.

b. *Usable temperatures:* The operating temperature range is not specified.

c. *Chemical composition:* This liquid is a refined petroleum base liquid with additives to improve oxidation resistance and wear (tricresyl phosphate, 0.5 ± 0.1 percent by weight as the antiwear agent). The finished product shall contain no pour point depressants, viscosity index improvers, admixtures of resins, rubber, soaps, gums, fatty oils, oxidized hydrocarbons, nor other additives not specifically approved.

d. *Uses:* This liquid is designed for use in missile hydraulic systems applications at ambient temperatures below 20°F .

e. *Limitations:* This liquid is not for high temperature or high load applications. It is not interchangeable with Hydraulic Fluid, Castor Oil Base (blue color), Specification MIL-H-7844. This liquid shall not be mixed with, but may be substituted for, Hydraulic Fluid, Petroleum Base, Specification MIL-H-5606B, for low temperature operation.

f. *Custodian:* Army-MR

MIL-H-46001A: HYDRAULIC FLUID, PETROLEUM BASE, FOR MACHINE TOOLS, TYPES I, II, III, AND IV	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR
Pour Point, °F (Max): Type I	+10
Type II	+10
Type III	+10
Type IV	+20
Flash Point, °F (Min): Type I	325
Type II	325
Type III	350
Type IV	375
Viscosity, cSt: 100°F Type I	30-37
Type II	42-52
Type III	62-70
Type IV	106-121
Viscosity Index: (Min)	80
Neutralization No.: mg KOH/g (Max)	0.20
Additives:	Approval Req'd
Oxidation Stability: Bare Steel Strip	0.20
168 hr at 212°F Copper Strip	0.20
Max wt Chg, Pitting, Etch and Corr. at 20X	None
mg/cm ² % Visc. Chg at 100°F (Max)	25.0
Neutral. No. Chg (Max)	+0.15
Precipitation No. (Max)	0.05
Insoluble Mat'l or Gummy	None
Compatibility:	All Fluids to This Spec.
Water Content:	None
Foaming: 75°F, after 5.0 min blowing, ml (Max)	No limit
75°F, after 10.0 min settling, ml (Max)	100
200°F, after 5.0 min blowing, ml (Max)	No limit
200 °F, after 10.0 min settling, ml (Max)	25
Repeat 75°F test	Same as init. 75°F Test
Emulsion: After 30 min settling; foam or cuff (Max)	3.0 ml
(Oil and Water, 130°F, 5.0 min stir, 30 min settling)	Trace
Copper Corr.: 168 hr at 212°F	No Pit or Etch
Rust Prevention: (bare steel), 24 hr at 130°F	None
Recommended Temperature Range, °F:	NR
NATO Symbol:	None
Storage Stability:	NR
Notes: NR, no requirements.	
Use: Hydraulic systems of metal working machine tools.	

MIL-L-46002(ORD): LUBRICATING OIL, CONTACT AND VOLATILE, CORROSION INHIBITED	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR
Pour Point, °F (Max):	-50
	-10
Flash Point, °F (Min):	240
	250
Viscosity, cSt: -40°F (Max)	10,000
-40°F (Max)	NR
100°F (Min)	12
100°F (Min)	95 to 125
210°F	NR
210°F	9.65 to 12.98
Precipitation No.: ml/10 ml (Max)	0.05
Hydrocarbon Solubility: 24 hr at 77°F	No Separation
Corrosive Protection: Humidity Cabinet, 300 hr at 120°F	No Corrosion
Vapor Phase; 6 hr at 40°F	
and 18 hr at 130°F	No Corrosion
Vapor Phase Prot. after exhaustion;	
6 hr at 210°F	No Corrosion
Acid Neut.: 77°F, acid sol. dip, 4 hr in oil; % Corr.	No Corrosion
Water Displacement/Stability: 1.0 hr at 77°F	No Corrosion
Corrosion Immersion: Aluminum	0.20
7 days at 130°F Steel	0.50
Max wt Chg; mg/cm ² Copper	1.50
Evaporation: % wt Volatile matter (Max), Grade 1	15.0
(210°F) % wt Volatile matter (Max), Grade 2	5.0
% Visc, Chg at 100°F, Grade 1	-5 to +20
% Visc, Chg at 100°F, Grade 2	-5 to +20
NATO Symbol:	None
Storage Stability:	--
Recommended Temperature Range, °F:	Up to 130
Compatibility:	Not Interchangeable
Notes: NR, no requirements. --, no information. Use: Preservative oil for closed systems, both as vapor and contact lub. Not recommended as an operational oil.	

MIL-H-46004(ORD): HYDRAULIC FLUID, PETROLEUM BASE, MISSILE	
PROPERTIES	VALUES
Color:	Yellow (Clear and Transparent)
Specific Gravity:	Report
Pour Point, °F (Max):	-75
Flash Point, °F (Min):	200
Viscosity, cSt: -65°F (Max)	300
-40°F (Max)	75
100°F (Min)	2.8
Neutralization No.: mg KOH/g (Max)	0.20
Additives: Antiwear (tricresyl phosphate), % wt	0.5 ±0.1
Oxid Inhibitors, % wt	≤ 2.0
Pour Point Depressant, % wt	None
Viscosity Improvers, % wt	None
Others	Approval Req'd
Precipitation No.:	0
Water Content, % (Max):	0.015
Corr. and Oxid. Stability: Steel	±0.20
168 hr at 250°F Aluminum Alloy	±0.20
Max wt Chg, mg/cm ² Magnesium Alloy	±0.20
Cad.-Plate	±0.20
Copper	±0.60
Pitting, Etch and Corr at 20X	None
% Visc Chg at 100°F	-5 to +20
Neutral. No. Increase (Max)	0.20
Insoluble Mat'l or Gunning;	
% wt	None
Copper Corr: 72 hr at 212°F	Slight Stain; no Pits
Low Temperature Stability: 72 hr at -65°F	No Solids, nongel
Rubber Swell: Type "L," Vol Chg; %	19-26.5
Solid Particle Content: 5-15 Microns	2,500
(Max Parts/100 ml) 16-25 Microns	1,000
26-50 Microns	250
51-100 Microns	25
Over 100 Microns	2
Evaporation: 4 hr at 150°F	Oily, nontacky
Corrosivity: brass-steel, 10 days, 75°F, 50% R.H.	No Corrosion
Recommended Temperature Range, °F:	< 20
NATO Symbol:	None
Storage Stability:	--
Compatibility:	Not Interchangeable
Water Stability: 1 hr at 77°F, 50% R.H.	--
Humidity Cabinet: 8 days, 50% R.H.	--
Machine Gun Test: -75°F, 25 Rounds	--
Notes:	
--, no information.	
Use: Guided missile hyd. systems at low temperature. Substitute for MIL-H-5606B.	

MIL-H-81019(WEP): HYDRAULIC FLUID, PETROLEUM BASE, ULTRA - LOW TEMPERATURE

(NATO Symbol: None)

a. *General characteristics:* This liquid is a very low temperature, petroleum base, hydraulic fluid containing specified additives. The fluid has a -90°F pour point and 12-month storage life.

b. *Usable temperature:* The operating temperature range is -90° to +210°F.

c. *Chemical composition:* This liquid has a petroleum base, is clear and transparent, and contains additives to improve viscosity-temperature characteristics, oxidation resistance, and antiwear properties.

d. *Uses:* Automatic pilots, shock absorbers, aircraft brakes, flap-control mechanisms, missile hydraulic servo-controlled systems, aircraft and ordnance hydraulic systems, and other hydraulic systems using synthetic sealing materials.

e. *Limitations:* This fluid is not compatible with any type or grade of hydraulic fluid other than MIL-H-5606B which is to be substituted only in emergencies.

f. *Custodians:* Navy-WP

Air Force-11

MIL-H-19457B(SHIPS): HYDRAULIC FLUID, FIRE RESISTANT

(Type I - Low Viscosity; NATO Symbol, H-580)

(Type II - High Viscosity)

a. *General characteristics:* These liquids are two-viscosity grades of nonpetroleum base fire resistant hydraulic fluids for high pressure hydraulic systems and air compressors.

b. *Usable temperatures:* The operating temperature range is not specified, but the liquid is intended for low ambient temperatures (above 25°F for Type I and above 40°F for Type II), and for moderate high temperatures to roughly 200°F. The minimum compression combustion ratio is 42.0.

c. *Chemical composition:* These oils are stable homogeneous fluids of phosphoric acid base and such other ingredients as are required for conformance with this specification. They shall contain 10 ppm by weight of Petrol Green D dye for identification.

d. *Uses:* These oils are fire-resistant fluids for hydraulic systems at moderate temperature ranges, and also for use in air compressors. They may be used as lubricants for angular contact ball bearings and should provide at least 50 percent as good a bearing life as Lubricating Oil, Military Symbol 2110H (MIL-L-15017). They are compatible with butyl rubber seals and packing.

e. *Limitations:* Material qualified under MIL-H-19457B(SHIPS) has a low ortho isomer content in order to pass the specification toxicity requirements. The Bureau of Medicine and Surgery has approved the shipboard use of these qualified products as a result of careful consideration by a committee of competent toxicologists. Containers must be properly marked with warning labels as required by the specification.

f. *Custodian:* Navy-SH

MIL-H-8446B: HYDRAULIC FLUID, NONPETROLEUM BASE, AIRCRAFT

(NATO Symbol: None)

a. *General characteristics:* This oil is a wide temperature range, nonpetroleum base, hydraulic fluid that has good oxidation stability and antiwear properties.

b. *Usable temperatures:* The specified operating temperature range is -65° to +400°F (Type III aircraft hydraulic systems).

c. *Chemical composition:* This liquid is a nonpetroleum synthetic base oil with additives to impart oxidation stability, antiwear properties, and viscosity-temperature characteristics necessary to meet the requirements of this specification. Certain disiloxanes containing additives are satisfactory for the rubber swell requirements.

d. *Uses:* This hydraulic fluid is intended for use in high-temperature aircraft hydraulic systems (Type III aircraft hydraulic system as defined in Specification MIL-H-5440), and other systems where a high quality hydraulic fluid is required.

e. *Limitations:* The fluid has good storage life and has satisfactory rubber swell properties for type "S" synthetic rubber. It is compatible with other hydraulic fluids to this specification, but not interchangeable with any others. The toxicity characteristics must be furnished.

f. *Custodians:* Army-MR

Navy-WP

Air Force-11

MIL-L-6085A: LUBRICATING OIL; INSTRUMENT, AIRCRAFT, LOW VOLATILITY

(NATO Symbol: None)

a. *General characteristics:* This oil is a low volatility, nonpetroleum base lubricating oil with wide temperature, corrosion, and oxidation properties.

b. *Usable temperatures:* The operating temperature range is not specified.

MIL-H-81019(WEP): HYDRAULIC FLUID, PETROLEUM BASE, ULTRA-LOW TEMPERATURE	
PROPERTIES	VALUES
Color:	Clear and Transparent
Specific Gravity:	NR
Pour Point, °F (Max):	-90
Flash Point, °F (Min):	200
Viscosity, cSt: -90°F (Max)	6,000
-80°F (Max)	2,500
-65°F (Max)	800
-40°F (Max)	200
130°F (Min)	5
210°F (Min)	2.5
Neutralization No.: mg KOH/g (Max)	0.20
Additives: Antiwear (tricresyl phosphate), % wt	0.50 ± 0.1
Oxidation Inhibitor, % wt	≤ 2.0
Corrosion Inhibitor, % wt	As Req'd
Viscosity Improver, % wt	≤ 10.0
Corr. and Oxid. Stability: Steel	± 0.20
168 hr at 250°F Aluminum Alloy	± 0.20
Max wt Chg, Magnesium Alloy	± 0.20
mg/cm ² Cad.-Plate	± 0.20
Copper	± 0.60
% Visc Chg at 130°F	-5 to +20
Pitting, Etch or Corr. at 20X	None
Increase in Neutral. No. (Max)	0.20
Insoluble Mat'l or Gummy	None
Low Temperature Stability: 72 hr at -65°F	No Solids, nongel
Shear Stability: Visc. Chg at 130°F (Max)	< Ref. Fluid
(30 min sonic oscil.) Visc. Chg at -40°F (Max)	< Ref. Fluid
Neutral. No. Chg (Max)	≤ + 0.20
Evaporation: 4 hr at 150°F	Oily nontacky
Copper Strip. Corr.: 72 hr at 250°F (Max)	No. 2 (ASTM)
Solid Particle Content: 5-15 Micron	2,500
(Max Parts/100 ml) 16-25 Micron	1,000
26-50 Micron	250
51-100 Micron	25
Over 100 Micron	None
Foaming: (75°F); after 5.0 min blowing; ml (Max)	65
after 10.0 min settling; ml (Max)	None
Rubber Swell: Type "L", Vol Chg, %	19-28
Water Content: % (Max)	0.01
Storage Stability: (-80° to 120°F) Months; (Min)	12
Recommended Temperature Range, °F:	-90 to +210
Compatible Hyd Fluids: (Emergency Only)	MIL-H-5606B
NATO Symbol:	None
Corr. Inhib. (humidity): 20 hr at 72°F (bare steel)	--
Corrosivity (brass and steel): 10 days at 80°F	--
Wear (Steel): Shell 4-Ball; (2 hr 167°F, 40 kg, 1,200 rpm); Scar Dia	--
Notes: NR, no requirements. --, no information.	
Use: Auto-pilots, shock absorbers, brakes, flap-control mech., missile hyd. servo-control and other systems using synthetic seals.	

MIL-H-19457B(SHIPS): HYDRAULIC FLUID, FIRE RESISTANT		
PROPERTIES	Type I Low Viscosity	Type II High Viscosity
Color:	Green	Green
Pour Point, °F (Max):	0	25
Viscosity, cSt: 100°F	43-50	125-135
210°F (Min)	4.8	6.3
Neutrality (Qualitative): Methyl Orange	Neutral (Yellow)	Neutral (Yellow)
Neutralization No. (Acid): mg KOH/g (Max)	0.10	0.10
Evaporation: 22 hr at 210°F, % wt Loss (Max)	0.30	0.30
Foaming Tendency: at 75°F	No Limit	No Limit
Foam Stability: 10 min after collapse, ml foam (Max)	300	300
Emulsion Test: 130°F, Settling time, min (Max)	30	30
Precipitation No.: (90-95°F), ml (Max)	0.01	0.01
Specific Gravity:	No Limit (Record)	No Limit (Record)
Refractive Index, n_d at 20°C	No Limit (Record)	No Limit (Record)
Corrosion: Brass	±0.2	±0.2
7 days at 130°F Zinc	±0.2	±0.2
Max wt chg, Steel	±0.2	±0.2
mg/cm ² Aluminum	±0.2	±0.2
Visual Pitting or Etch.	None	None
Compatibility with Packings:	Any suitable for TCP	Any suitable for TCP
Butyl Rubber Swell: % vol chg	±5.0 of TCP	±5.0 of TCP
Fire Resistance: CFR Compression Ratio (Min)	42:1	42:1
Viscosity Shear Stability: Visc chg at 100°F (Max)	-10%	-10%
5,000 cycles, 1,000 psi Visual Separation	None	None
at 100°F Visual Decomposition	None	None
Sludging	None	None
Neutralization (Acid) No.: mg KOH/g (Max)	0.5	0.5
Bearing Lub., 208 Ball Bearing: 4,600 lb & 1,750 rpm (life)	≤50% Symbol 2110H	≤50% Symbol 2110H
Hydrolytic Stability: Copper; wt Loss; mg/cm ² (Max)	0.3	0.3
48 hr at 200°F Copper, Visual Corr	None	None
and 5 rpm Water layer acidity: mg/KOH (Max)	5.0	5.0
Acid No. Chg of Fluid; mg KOH/g fluid	±0.2 Max	±0.2 Max
Insolubles, % (Max)	0.5	0.5
Handling Properties:	Toxic *	Toxic *
NATO Symbol:	H-580	None
Recommended Operating Temp Range, °F: Low	>25	> 40
High	160-210	160-210
Storage Stability:	--	--
Compatibility: Other Fluids	--	--
Base Fluid:	Phosphorus Ester	Phosphorus Ester
Notes: --, no information.		
*Material qualified under MIL-H-19457B(SHIPS) has a low ortho isomer content in order to pass the specification toxicity requirement. The Bureau of Medicine and Surgery has approved the shipboard use of these qualified products as a result of careful consideration by a committee of competent toxicologists. Containers must be properly marked with warning labels as required by the specification.		
Use: Hydraulic systems and air compressors where fire resistant fluid is needed.		

MIL-H-8446B: HYDRAULIC FLUID, NONPETROLEUM BASE, AIRCRAFT	
PROPERTIES	VALUES
Color:	NR
Pour Point, °F (Max):	-75
Flash Point, °F (Min):	395
Autogenous Ignition Temp, °F (Min):	700
Viscosity, cSt: -65°F (Max)	2,500
100°F	Report
210°F	Report
400°F (Min)	2.5
Vapor Pressure at 400°F: mm of Hg (Max)	5.0
Water Content, % wt (Max):	0.010
Density, at 60°F, (g/cc):	Report
Specific Heat (Btu/lb °F): 100°F	Report
200°F	Report
300°F	Report
400°F	Report
Thermal Conductivity, Btu/(hr)(ft ²)(ft/°F): 100°F	Report
200°F	Report
300°F	Report
400°F	Report
Low Temp Stability: 72 hr at -65°F	Nongel, No Solids
Corr and Oxid Stability: Steel	±0.2
72 hr at 400°F Aluminum	±0.2
Max wt chg, Copper	±0.4
mg/cm ² Silver	±0.2
Pitting, Etch or Corr at 20X	None
% Visc Chg at 210°F (Max)	±35.0
Acid No. mg KOH/g (Max)	1.0
Insoluble Mat'l or gumming	None
Hydrolytic Stability: Copper wt chg: mg/cm ² (Max)	±0.50
48 hr at 200°F Copper Pit or Etch	None
and 5 rpm Copper Corrosion (Max)	No. 1 (ASTM)
Acid No. Water; mg KOH/g (Max)	0.50
Acid No. Oil; mg KOH/g (Max)	0.50
Visc Chg of Oil at 210°F, % (Max)	±20.0
Insoluble mat'l; % wt (Max)	0.50
Rubber Swell: 70 hr at 250°F; Type "S," % Vol Chg	+15 to +25
Foaming: Oil and foam after 5.0 min blowing, ml (Max)	60.0
(200 ml sample) Foam Collapse Time, Min (Max)	10.0
Shear Stability: Visc Decrease at 210°F	≤ MIL-F-5602
(5,000 cycles, 2,500 psi, 275°F) Acid No. Increase (Max)	0.50
Wear Test (200 hr, 275°F, 3,000 psi and 3,600 rpm):	≤ MIL-H-5606B
Compatibility:	All Fluid to Spec.
Storage Stability: 12 months, dark storage	No Sludge or Separation
Recommended Operating Temp Range, °F:	-65 to 400
NATO Symbol:	None
Notes: NR, no requirements.	
Report, no limit, report data.	
Use: High temperature aircraft hydraulic systems and other systems requiring wide temperature, stable hydraulic fluid.	

MIL-L-6085A: LUBRICATING OIL, INSTRUMENT, AIRCRAFT, LOW VOLATILITY	
PROPERTIES	VALUES
Color:	Clear: < No. 5 (ASTM)
Pour Point, °F (Max):	-70
Flash Point, °F (Min):	365
Viscosity, cSt:	12,000
-65°F (Max)	8.0
130°F (Min)	
Additives: Oxidation Inhibitors, % wt	Allowed
Corrosion Inhibitors, % wt	Allowed
Viscosity Improvers, % wt	None
Pour Point Depressant, % wt	None
Acid or Neutralization No.: mg KOH/g (Max)	Report
Precipitation No.: (Min)	0
Evaporation: 22 hr at 210°F, % wt Loss (Max)	1.0
Corr. and Oxid. Stability: Steel	±0.2
168 hr at 250°F Aluminum	±0.2
Max wt chg, Magnesium	±0.2
mg/cm ² Cad.-Plate	±0.2
Copper	±0.2
Pitting, Etch. or Corr. at 20X	None
Viscosity Chg at 130°F, % (Max)	±5.0
Neutralization No. Increase "	0.50
Low Temp Stability: 72 hr at -65°F	Nongel, No Separation
Protection: 5 Bare steel panels; 100 hr at 77°F and 100% R.H. (4 out of 5 panels must pass)	Corr. Area < 2 mm Dia
Corrosivity Test: (10 days, 80°F, 50% R.H.)	≤ 2 Spots 1-2 mm Dia
3 spec. (Brass clip and steel disc): Corr. at 10X	No Corr. on 2 Spec.
Recommended Operating Temp Range, °F :	≤ 3 spots under clip; 1 Spec.
NATO Symbol:	-65 to 350
Storage Stability:	None
Compatibility:	--
Synthetic Oil Base	--
	Carboxylic Acid Ester
Notes: --, no information.	
Report, no limit, report data.	
Use: Low evaporation oil for aircraft instruments, electrical equipment and mechanical equipment where wide temperature and oxidation and corrosion protection are needed.	

c. *Chemical composition:* This oil is a synthetic base oil (carboxylic acid ester) with additives to impart oxidation stability and corrosion protection properties. It contains no pour point depressants or V.I. improvers.

d. *Limitations:* The finished fluid must contain no resins, gums, rubber, fatty oils, oxidized hydrocarbons, or other additives not approved by the qualifying agency. Containers for the fluid must have a warning note that this fluid may soften paint, natural rubber, or neoprene.

e. *Custodians:* Army-MR
Navy-WP
Air Force-11

**MIL-L-7808G: LUBRICATING OIL, AIRCRAFT
TURBINE ENGINE, SYNTHETIC
BASE**

(NATO Symbol: 0-148)

a. *General characteristics:* This oil is a nonpetroleum base lubricating oil for aircraft turbine engines and similar equipment. It has good storage, wide temperature, and environment limits.

b. *Usable ambient temperatures:* The operating temperature range is not specified, but the nominal operating temperature range is -65°F to 300°F.

c. *Chemical composition:* It shall be a synthetic base fluid (carboxylic acid ester) but additives to impart oxidation stability, corrosion-preventive properties, and antiwear properties are permitted.

d. *Uses:* This oil is intended as a lubricating oil in specific models of aircraft turbine engines, helicopter transmissions, and similar equipment.

e. *Limitations:* This oil should not be mixed with any oils other than MIL-L-7808 oils and revisions thereto. If the oil contains tricresyl phosphate additive, the supplier must certify that it contains less than 1.0 percent of the ortho isomer.

f. *Custodians:* Army-MR
Navy-WP
Air Force-11

**MIL-L-23699A: LUBRICATING OIL, AIRCRAFT
TURBOPROP AND TURBOSHAFT
ENGINES, SYNTHETIC BASE**

(NATO Symbol: None)

a. *General characteristics:* This oil is a nonpetroleum base oil similar to MIL-L-7808G but with higher pour and flash points.

b. *Usable ambient temperatures:* The operating temperature range is not specified, but the nominal range is -40° to +400°F.

c. *Chemical composition:* The composition of this synthetic base oil is not limited, except that metal organic compounds of titanium are prohibited. The oil may contain tricresyl phosphate as an antiwear additive.

d. *Uses:* This oil has a higher viscosity than MIL-L-7808G and is intended for use in aircraft turboprop and turboshaft engines, helicopter transmissions, and other systems where MIL-L-7808G has been used previously.

e. *Limitations:* Because of the higher viscosity, this oil may not be suitable below -40°F. If tricresyl phosphate antiwear additive is used, it shall not contain more than 1.0 percent of ortho isomer. Oil container should have the following note: "Do not mix oils other than MIL-L-23699 and revisions thereto".

f. *Custodian:* Navy-WP

**MIL-S-81087A(ASG): SILICONE FLUID, CHLO-
RINATED PHENYL METHYL
POLYSILOXANE**

(NATO Symbol: None)

a. *General characteristics:* This liquid is a dual class silicone base liquid for lubrication and other applications over a wide temperature range. It has good thermal stability.

b. *Usable ambient temperatures:* Type I: In air (oxygen) environment this fluid is suitable for -100° to 425°F usage. In an inert atmosphere this fluid is suitable for -100° to 500°F conditions. Type II: This fluid contains an oxidation inhibitor and in both an air environment and an inert atmosphere it is suitable for -100°F to 500°F conditions.

c. *Chemical composition:* Type I fluid is a copolymer containing only dimethyl siloxy and methyl chlorophenyl siloxy units, with trimethyl siloxy terminal groups. Type II fluid is a Type I fluid with the addition of an oxidation inhibitor for high temperature stability in oxidizing atmospheres. Any other additives in either Type I or Type II requires prior approval of the qualifying agency.

d. *Uses:* This liquid is used for lubricating, hydraulic, damping, and related applications over a wide temperature range. Applications are: hydraulic systems and servomechanisms; crankcases and gear boxes for mechanical devices and compressors, engines, and pumps; ball, sleeve and pivot bearings in instruments; electronic equipment and electric motors, etc.; clocks and timing devices; and fluid transmissions.

e. *Limitations:* Type II fluid, when exposed to temperatures above 500°F in an inert atmosphere, has

MIL-L-7808G: LUBRICATING OIL, AIRCRAFT TURBINE ENGINE, SYNTHETIC BASE	
PROPERTIES	VALUES
Color:	Transparent, ≤ No. 3 ASTM
Pour Point, °F (Max):	-75
Flash Point, °F (Min) (COC) :	400
Viscosity, cSt: 100°F (Min)	11.0
210°F (Min)	3.0
Viscosity Stability, cSt: (3 hr at -65°F)	<13,000
(72 hr at -65°F)	<17,000
Additives: Oxidation Inhibitor, % wt	Allowed
Corrosion Inhibitor, % wt	Allowed
Antiwear (Tricresyl Phosphate), % wt	Allowed
TCP, ortho isomer content, % wt	≤1.0
Acid No.: mg KOH/g (Max)	0.30
Evaporation: wt loss, % (Max); (6.5 hr at 400°F)	35.0
Trace Sediment: ml/200 ml (Max)	0.005
Corr. and Oxid. Stability: Steel	±0.2
72 hr at 347°F Silver	±0.2
Max wt Chg, Aluminum	±0.2
mg/cm ² Magnesium	±0.2
Copper	±0.4
Pitting, Etch. or Corr. at 20X	None
Visc Chg at 100°F; %	-5 to +15
Acid No. Increase (Max)	2.0
Silver and Copper Corr.: (50 hr at 450°F), wt loss; mg/in ²	≤3.0
Lead Corr.: (1.0 hr at 325°F) wt loss, mg/in ²	≤6.0
Deposition No.: Average of 4 test (Max)	3.5
Individual Test (Max)	4.25
Rubber Swell: Syn. Type H; % vol increase	12 to 15
Foaming: 75°F, 5 min blowing, ml foam (Max)	25
75°F, 3 min settling, ml foam (Max)	None
200°F, 5 min blowing, ml foam (Max)	25
200°F, 3 min settling, ml foam (Max)	None
75°F, 5 min blowing, ml foam (Max)	25
75°F, 3 min settling, ml foam (Max)	None
Storage Stability: (2 days at 230°F) Lead Corr. Value, mg/in ²	≤25
(7 days at 230°F) Lead Corr. Value, mg/in ²	≤150
12 months, 75°F, dark room	No Separation and Spec. Test
100-hr Engine Test: Engine rating (Min)	2.83
Filter wt increase; lb/hr (Max)	0.020
Average Oil Consumption; lb/hr (Max)	1.25
Compatibility: (Oils to this spec and others)	MIL-L-25336 MIL-L-9236 MIL-C-8188 MIL-O-6081 (Grade 1010) ≤68.0 0-148 -65 to 300 Carboxylic Acid Ester
Load Carrying (Ryder Gear Test): % Ref Oil "B"	
NATO Symbol:	
Recommended Operating Temp Range, °F:	
Synthetic Oil Base:	
Use: Specific aircraft turbine engines, helicopter transmissions and similar systems.	

MIL-L-23699A: LUBRICATING OIL, AIRCRAFT TURBOPROP AND TURBOSHAFT ENGINES, SYNTHETIC BASE	
PROPERTIES	VALUES
Color:	NR
Pour Point, °F (Max):	-65
Flash Point, °F (Min):	450
Viscosity, cSt: -40°F (Max)	13,000
100°F (Min)	25
210°F	5.0 - 5.5
Viscosity Stability: (72 hr at -40°F, % chg) (Max)	6.0
Neutralization or Acid No.: mg KOH/g (Max)	0.50
Fluid Composition	Syn.; No Limit
Additives: Metalorganic titanium compounds	None
TCP (ortho isomer cont.) %	≤ 1.0
Evaporation: 6.5 hr at 400°F, % wt Loss (Max)	10.0
Trace Sediment: 7 days at 75°F, ml/200 ml (Max)	0.005
Lead Corrosion: 1.0 hr at 325°F, wt Loss, mg/in ² (Max)	6.0
Rubber Swell: "H" Syn., 72 hr at 158°F, % vol	10 - 25
"F" Syn., 72 hr at 400°F, % vol	10 - 25
Foaming: (a) 75°F, 5.0 min blowing, ml (Max)	25
75°F, 1.0 min settling, ml (Max)	None
(b) 200°F, 5.0 min blowing, ml (Max)	25
200°F, 1.0 min settling, ml (Max)	None
(c) Repeat Sequence (a)	Same as (a)
Storage Stability: 48 hr at 230°F, mg/in ² (Max)	25.0
(Lead Corr., wt Loss) 168 hr at 230°F, mg/in ² (Max)	150.0
Low Temp Storage: 6 wk at 0°F	Noncryst., nongel
Extended Storage: 12 month at 75°F	All Spec. Tests
Thermal Stability: (24 hr at 500°F), 100°F Visc chg, %	≤ 5.0
Neutralization No. chg (Max):	2.0
Corr. & Oxid. Stability: Steel	±0.2/±0.2/Report
72 hr at 375°F/400°F/425°F Silver	±0.2/±0.2/Report
wt chg; mg/cm ² (Max) Aluminum	±0.2/±0.2/Report
Magnesium	±0.2/±0.2/Report
Copper	±0.4/±0.8/Report
Viscosity chg, %	-5 to 15/-5 to 25/Report
Neutralization No. chg, %	2.0/3.0/Report
Sludge after 400°F test, g/100 ml (Max)	1.0
Load Carrying; Ryder Gear Test: % Ref. Oil "B" (Min)	88.0
Bearing Test: Deposit Demerit Rating (Max)	80.0
(100 hr at 280°F) Filter Deposit, g (Max)	3.0
Viscosity chg at 100°F, %	-5 to 25
Neutralization No. chg (Max)	2.0
Total Oil Consumption, ml (Max)	2,000
Shear Stability: (Sonic), 30 min at 100°F; Visc. chg, % (Max)	-4.0
Turboprop Engine & Helicopter Trans. Test:	Select by Qual. Agency
NATO Symbol:	None
Recommended Operating Temp Range, °F:	-40 to 400
Notes: NR, no requirements. Report, no limits, but data reported.	
Use: Aircraft turbojet engines, helicopter transmissions, and other systems requiring high performance lubricating oils.	

MIL-S-81087A(ASG): SILICONE FLUID, CHLORINATED PHENYL METHYL POLYSILOXANE		
PROPERTIES	TYPE I VALUES	TYPE II VALUES
Color:	≤ Gardner Std. No. 1	Dark Amber or Brown
Specific Gravity (77°/77°F):	1.03 to 1.06	1.03 to 1.06
Pour Point, °F (Max):	-100	-100
Flash and Fire Point, °F (Min):	550 and 640	550 and 640
Viscosity, cSt: -65°F (Max)	3,500	3,500
100°F (Min)	50	50
210°F (Min)	15	15
Additives: Oxidation Inhibitor	None	Required
Others	Approval Req'd.	Approval Req'd.
Acid or Neutralization No.: mg KOH/g (Max)	0.05	0.10
Volatility: 24 hr at 302°F, % wt, Loss (Max)	1.0	1.0
Gel Time (Nonflow): 482°F, hr (Min)	72	1,500
Lubricity (Shell 4-Ball): AISI 52100 (Grade I), 77°F, 600 rpm, 50 kg, 1.0 hr: Scar Dia., mm (Max)	0.60	0.60
Oxid. & Corr. Stability: Aluminum Alloy	±0.10	±0.10
72 hr at 400°F (Type I) St Steel, Type 325	±0.10	±0.10
and 500°F (Type II): Titanium	±0.10	±0.10
Max wt chg, mg/cm ² : 99.9 Anode Silver	±0.10	±0.10
Mild Steel	±0.10	±0.10
Visc chg at 100°F, % (Max)	10	30
Acid No. Increase: (Max)	0.20	0.40
Solid Particle Content: Particle Size, 10-20 Micron	2,000	2,000
20 ml Sample, Max	300	300
number of particles	80	80
	40	40
	20 (No	20 (No
	Metal)	Metal)
	0	0
Compatibility:	No other lub. or hyd. oil	No other lub. or or hyd. oil
NATO Symbol:	None	None
Storage Stability:	--	--
Recommended Operating Temp Range, °F: (Air)	-100 to 425	-100 to 500
(Inert)	-100 to 500	-100 to 500
Foaming:	NR	NR
Rubber Swell:	NR	NR
Notes: --, no information. NR, no requirement.		
Use: Lubrication, hydraulic systems, damping and transmission fluid, etc., over wide temperature range.		

a tendency for the oxidation inhibitor to separate forming a soft gelatinous sludge or precipitate which will not decrease lubricity, but may cause a pressure drop in systems having filters or small orifices. Type II should be reserved for severe and relatively continuous oxidizing environments. Neither type should be mixed with any other lubricating oil or hydraulic fluid. When replacing another oil with this fluid, parts must be disassembled and cleaned with solvents.

f. *Custodian:* Navy-WP

VV-D-001078(GSA-FSS): DAMPING FLUID, SILICONE BASE (DIMETHYL POLYSILOXANE)

<i>NATO Symbol:</i>	<i>Grade (cSt)</i>
S-1714	10
S-1718	50
S-1720	100
S-1724	7,500
S-1726	20,000
S-1728	100,000
S-1732	200,000

a. *General characteristics:* This specification includes dimethyl polysiloxane base damping fluids having a wide range of viscosities—from 0.65 through 200,000 cSt at 77°F. The wide viscosity range of these fluids permits them to have many applications. This specification supersedes MIL-S-21568A which covered a similar class of damping fluids.

b. *Usable temperatures:* These fluids are usable from -65° to 600°F depending on the pour and flash points, and upon the viscosity grade selected.

c. *Chemical composition:* These silicone fluids—based on dimethyl polysiloxane—must be of high quality, meet the requirements of this specification, be free of suspended matter and water or sediment, and contain no admixture of other fluids which are not approved.

d. *Uses:* These multi-grade fluids are intended for many uses such as damping fluids, transducer fluids, lubricants, heat transfer fluids, dielectric fluids, mold release agents, water repellents, hydraulic fluids, protective dressings, and impregnants.

e. *Limitations:* These fluids should not be mixed with any other type of lubricating oil or hydraulic fluid. When replacing another oil with this fluid, parts must be disassembled and thoroughly cleaned with fresh solvent. Consideration must be given to the type of elastomer used in contact with the fluids because they tend to cause certain elastomers to shrink and harden. This is particularly true of the lower viscosity fluids.

f. *Custodian:* Navy-WP

MIL-H-5559A(WEPS): HYDRAULIC FLUID, ARRESTING GEAR

(NATO Symbol: None)

a. *General characteristics:* This specification covers the requirement for one type and one grade of non-petroleum base hydraulic fluid containing two corrosion inhibitors.

b. *Usable temperatures:* As an undiluted liquid, this fluid has ambient temperature limits from 0°F (freezing point) to approximately 329°F (boiling point). Lower freezing point temperatures may be obtained by the addition of water.

c. *Chemical composition:* This liquid has an ethylene glycol base and contains two corrosion inhibitors—triethanolamine phosphate and sodium mercaptoben-zothiozole.

d. *Uses:* This liquid is intended primarily for use in aircraft arresting gear and similar hydraulic systems.

e. *Limitations:* This liquid is not interchangeable with any other type or grade of hydraulic fluid. Care may be required in packaging to prevent deterioration or damage during shipment or storage under normal environmental conditions since undiluted fluid will freeze at about 0°F.

f. *Custodians:* Navy-WP

Air Force-11

MIL-P-46046A(MR): PRESERVATIVE FLUID, AUTOMOTIVE BRAKE SYSTEM AND COMPONENTS

(NATO Symbol: None)

a. *General characteristics:* This specification covers one type, one grade, and three compositions of a castor oil base preservative hydraulic fluid.

b. *Usable ambient temperatures:* Temperature limits as a preservative fluid are not specified, but as a limited usage heavy duty brake fluid, it should be limited to temperatures above 0°F and to moderate climates.

c. *Chemical composition:* This castor oil base hydraulic fluid is prepared in three compositions containing different additives. Composition 1 contains a diluent (3-methoxy butanol-1), borax-glycol condensate, and an approved antioxidant. Composition 2 contains a diluent (β , β' -methoxy-methoxy ethanol), borax-glycol condensate, and an approved antioxidant. Composition 3 contains diluents (diethylene glycol monomethyl ether and ethylene glycol monobutyl ether), borax-glycol condensate, di-t-butyl-p-cresol, and m-cresol.

d. *Uses:* This fluid is intended for preserving automotive hydraulic brake systems of vehicles in storage.

VV-D-001078(GSA-FSS):
DAMPING FLUID, SILICONE BASE (DIMETHYL POLYSILOXANE)

Viscosity Grades, cSt, at 25°C (77°F)	0.65 cSt ±10 percent	2.0 cSt ±10 percent	10.0 cSt ±10 percent	20.0 cSt ±10 percent	50.0 cSt ±5 percent	100 cSt ±5 percent	200 cSt ±5 percent	500 cSt ±5 percent	1,000 cSt ±5 percent	5,000 cSt ±5 percent	7,500 cSt ±5 percent	12,500 cSt ±5 percent	20,000 cSt ±5 percent	40,000 cSt ±5 percent	60,000 cSt ±5 percent	100,000 cSt ±5 percent	200,000 cSt ±10 percent	Test Method
Viscosity- temperature (VTC) coefficient ±0.02	--	0.48	0.57	0.58	0.59	0.60	0.62	0.62	0.62	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	$VTC = 1 - \frac{Visc_{210^{\circ}F}}{Visc_{100^{\circ}F}}$
Specific gravity ±0.004 at 77°F/77°F	0.761	0.872	0.940	0.950	0.960	0.971	0.971	0.971	0.971	0.974	0.974	0.974	0.976	0.976	0.976	0.976	0.978	ASTM D 1298
Refractive index ±0.002 at 77°F	1.375	1.390	1.399	1.400	1.402	1.4033	1.4033	1.4033	1.4033	1.4035	1.4035	1.4035	1.4035	1.4035	1.4035	1.4035	1.4036	ASTM D 1747
Pour Point, °F, Max	-68	-66	-65	-65	-65	-53	-53	-53	-53	-48	-48	-48	--	--	--	--	--	Fed. Test Method Std. No. 791a; Method No. 201
Dielectric constant ±0.03 at 100 cycles and 73°F	2.18	2.50	2.65	2.68	2.72	2.75	2.75	2.75	2.75	2.76	2.76	2.76	2.77	2.77	2.77	2.77	2.78	ASTM D 150
Flash point, °F, Min	30	185	325	400	535	575	575	575	575	600	600	600	600	600	600	600	600	Fed. Test Method Std. No. 791a; Method No. 1103
Volatility, %, Max	--	--	--	--	--	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	Wt loss; 24 hr at 302°F
Neutralization No., mg KOH/g	← 0.05 →																	
NATO Symbol	--	--	S-1714	--	S-1718	S-1724	--	--	--	--	S-1724	--	S-1725	--	--	S-1728	S-1732	
Storage Properties	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	
Recommended Operating Temp, °F	← Ref. Pour Point (Max) and Flash Point (Min) →																	
Foaming	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	

--, no information.

MIL-H-5559A(WEPS): HYDRAULIC FLUID, ARRESTING GEAR	
PROPERTIES	VALUES
Color:	NR
Specific Gravity, 60°/60°F (undiluted)	1.111 to 1.123
Freezing Point, °F: (Undiluted)	~ 0
Boiling Point, °F (Min) (Undiluted)	329
Composition: Ethylene Glycol, % wt (Min)	93.95
Water, % wt	2.5 to 3.0
Triethanolamine Phosphate, % wt	2.25 to 2.75
Sodium Mercaptobenzothiazole, % wt	0.2 to 0.3
Phosphate Content (calculated as H ₃ PO ₄), % wt (Min)	0.56
Ash, % wt (Max):	0.52
Viscosity, cSt: 100°F (Min)	9.0
pH Value (50% aqueous sol.), 77°F:	7.2 to 7.8
Suspended Matter:	None
Storage Stability:	NR
Recommended Operating Temp Range, °F:	0 - 329
Foaming:	NR
Oxd. and Corr. Stability:	NR
NATO Symbol:	None
Compatibility:	No other type or grade
Rubber Swell:	NR
Notes: NR, no requirements.	
Use: Aircraft arresting gear and similar hydraulic systems.	

MIL-P-46046A(MR): PRESERVATIVE FLUID, AUTOMOTIVE BRAKE SYSTEMS AND COMPONENTS			
PROPERTIES	VALUES		
	Comp. I	Comp. II	Comp. III
Color:	NR	NR	NR
Specific Gravity; 68°/68°F:	0.9380-0.9420	1.009-1.015	0.9620-0.9680
Pour Point, °F (Max):	NR	NR	NR
Flash Point, °F (Min):	NR	NR	NR
Boiling Point, °F (760 mm):	315-324	320-332	332-367
Composition: Castor Oil, % wt	40.3 ±1.0	37.5 ±1.0	38.7 ±1.0
3-Methoxy Butanol-1, % wt	58.1 ±1.0	--	--
B,B'-Methoxy-methoxyethanol, % wt	--	60.9 ±1.0	--
Diethylene Glycol Monomethyl Ether, % wt	--	--	31.4 ±0.5
Borax-Glycol Condensate, % wt	1.4 ±0.1	1.4 ±0.1	2.1 ±0.2
Di-t-Butyl-p-Cresol, % wt	--	--	0.475 ±0.050
m-Cresol, % wt	--	--	0.025 ±0.005
Ethylene Glycol Monobutyl Ether, % wt	--	--	27.3 ±0.5
Antioxidant (Min)	0.2	0.2	--
pH Value:	10.2-11.0	8.8-9.6	9.9-10.7
Corrosiveness: Steel and Tinned Iron	0.1	0.1	0.1
120 hr at 210°F Aluminum Alloy	0.1	0.1	0.1
Max wt Loss, Cast Iron	0.1	0.1	0.1
mg/cm ² Brass	0.3	0.3	0.3
Copper	0.3	0.3	0.3
Pit & Etch of Metal Strips	None	None	None
Rubber Cups (Natural); Appearance	No Carbon Black	No Carbon Black	No. Carbon Black
Surface Condition	No	No	No
Swelling/in.	Tackiness 0.002-0.015	Tackiness 0.020-0.032	Tackiness 0.040-0.050
pH of Test Fluid (Min)	7.0	7.0	7.0
Condition of Test Fluid	No Gel/Sediment	No Gel/Sediment	No Gel/Sediment
Stability: Aluminum Alloy	0.05	0.05	0.05
72 hr at RT & 168 hr at 158°F Cast Iron	0.10	0.10	0.10
wt Loss, mg/cm ² (Max) Metal Pit or Etch	None	None	None
Excessive Gum Deposit	None	None	None
Storage Stability:	--	--	--
NATO Symbol:	None	None	None
Foaming:	--	--	--
Compatibility:	--	--	--
Viscosity, cSt:	NR	NR	NR
Recommended Operating Temp Range, °F:	> 0; NR	> 0; NR	> 0; NR
Notes: NR, no requirements. RT, room temperature --, no information.			
Use: Principal use preservative fluid for automotive hydraulic brake systems during storage and as packaging fluid.			

It is also a packaging fluid for both wheel and master cylinder assemblies. The fluid may also be used as an actuating fluid in test stands in checking hydraulic brake parts for flaws and defects. It may be used in vehicles in limited operation in moderate and warm climates.

e. *Limitations:* Avoid prolonged breathing of vapors from these fluids and use with adequate ventilation. Also avoid repeated or prolonged contact with skin.

f. *Custodian:* Army-MR

JAN-F-461: FLUID, SHOCK ABSORBER, HEAVY

(NATO Symbol: None; Military Symbol: SAH)

a. *General characteristics:* This specification covers a chemically treated, castor oil base liquid for rotary type hydraulic shock absorbers.

b. *Usable temperatures:* The specific temperature limits for this liquid are not specified but the pour point (maximum) is -25°F and the flash point (minimum) is 400°F. Because of viscosity characteristics, the liquid will function best at temperatures above 0° and below 200°F.

c. *Chemical composition:* This liquid is a castor oil chemically treated to produce proper characteristics. The liquid shall be free of acid, alkali, moisture, tarry or suspended matter, and other foreign matter. It may not contain any rosin or cottonseed oil.

d. *Uses:* This liquid is specifically intended for use as a heavy shock absorber fluid in Houdaille rotary-type shock absorbers. It also may have some usage as a damping or hydraulic actuating fluid.

e. *Limitations:* This liquid is not recommended for low temperature applications.

f. *Custodians:* Army-MR
Navy-SH

MIL-H-13910B: HYDRAULIC FLUID, POLAR-TYPE AUTOMOTIVE BRAKE, ALL-WEATHER

(NATO Symbol: None)

a. *General characteristics:* This specification covers one type and one grade of automotive hydraulic brake fluid for low temperature applications.

b. *Usable temperatures:* -67° to +131°F ambient.

c. *Chemical composition:* This specification does not limit the composition of this hydraulic fluid.

d. *Uses:* This liquid is recommended as an all-weather automotive hydraulic brake system fluid for ambient temperatures ranging from -67° to +131°F.

e. *Limitations:* It should not be used in preserving hydraulic brake parts and components in warehouse storage.

f. *Custodian:* Army-MR

VV-B-680a: BRAKE FLUID, AUTOMOTIVE

(NATO Symbol: H-542; Military Symbol: HB)

a. *General characteristics:* This specification covers one grade and type of hydraulic brake fluid.

b. *Usable temperatures:* Usable ambient temperature range of -40° to +131°F and usable operating liquid temperatures from -40° to +374°F. In practice, a low operating limit of -31°F is recommended. The viscosity at -31°F will be about 900 cSt.

c. *Chemical composition:* Composition of this fluid is not limited; however, to meet the specification requirements it will probably be necessary to employ a glycol or castor oil and glycol base fluid and approved additives.

d. *Uses:* This brake fluid is intended for use as an operating fluid in automotive hydraulic brake systems within the specified ambient or fluid temperature limits.

e. *Limitations:* This fluid is not to be used for preserving hydraulic brake system parts and components in storage, nor as an operating fluid in vehicle brake systems when the vehicle may be subject to prolonged standby storage.

f. *Custodians:* Army-MR
Navy-YD
Air Force-67

MIL-H-22072A(WP): HYDRAULIC FLUID, CATALPULT

(NATO Symbol: None)

a. *General characteristics:* This specification covers a fire-resistant water base hydraulic fluid containing additives for lubricity, corrosion prevention, and viscosity-temperature characteristics.

b. *Usable ambient temperatures:* Specification does not limit temperature range of this hydraulic fluid but, because of the high water content, it should be used for moderate ambient temperatures within the low temperature crystallization (+10°F) and the high temperature stability (+158°F) range.

c. *Chemical composition:* This specification does not limit the composition of this hydraulic fluid other than that it must contain 50 percent water and additives for lubricity, corrosion, and viscosity-temperature characteristics to meet the specification requirements.

JAN-F-461: FLUID, SHOCK ABSORBER, HEAVY	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR
Base Fluid:	Castor Oil
Additives: Acids	None
Alkali	None
Moisture	None
Suspended Matter	None
Thickeners	None
Rosin	None
Cottonseed Oil	None
Pour Point, °F: (Max)	-25
Flash Point, °F: (Min)	400
Viscosity, SUS: 100°F (Max)	1,500
210°F	140-150
Neutralization No.: mg KOH/g (Max)	3.0
Copper Strip Corr.: 3 hr at 212°F	No Corrosion
Reaction: Neutrality (Qualitative)	Neutral (Yellow)
Storage Stability:	--
Compatibility:	--
Recommended Ambient Temp Range, °F:	--
Rubber Swell:	--
Foaming:	--
NATO Symbol:	None
Military Symbol:	SAH
Notes: NR, no requirements. --, no information. Use: Rotary type (Houdaille) shock absorbers and as a damping or hydraulic fluid.	

MIL-H-13910B: HYDRAULIC FLUID, POLAR-TYPE AUTOMOTIVE BRAKE, ALL WEATHER	
PROPERTIES	VALUES
Color:	NR
Specific Gravity:	NR
Pour Point, °F:	<-67
Boiling Point, °F (Min):	309
Boiling Point Change, °F (Max):	+5
Flash Point, °F (Min):	145
Viscosity, cSt: -67°F (Max)	900
122°F (Min)	3.5
212°F (Min)	1.3
pH Value: (fluid-water-alcohol mixture)	8.0-11.0
Evaporation: (7 day, 212°F cycle) % wt Loss (Max)	80
Residue, Quality	Fluid & Oily
Precipitated Matter	Slight, Nongritty
Residue Properties, Pour Point, °F (Max)	27
Viscosity, cSt: 0°F (Max)	2,100
122°F (Min)	35
212°F (Min)	9
Low Temperature, Appearance:	Transparent
(144 hr at -67°F) Bubble Rise Time, sec (Max)	10.0
Fluid-Water Mixture: (24 hr at -67°F) Bubble Rise, sec (Max)	5.0
(24 hr at 140°F) Appearance	No Separation or Sediment
Rubber Swell: (120 hr at 158°F), Cup dia increase; in.	0.015 to 0.050
Hardness chg (durometer): points	-10 to +0
Rubber Condition	No Disintegration
Corrosiveness: Tinned Iron	0.2
120 hr at 212°F Carbon Steel	0.2
Max wt chg, Aluminum Alloy	0.1
mg/cm ² Cast Iron	0.2
Brass	0.4
Copper	0.4
Pit. & Etch. on Metal Strips	None
Rubber Cup Condition	No Disintegration
Max Cup dia increase, in.	0.050
Rubber hardness chg (durometer) points	<-15
pH Value (Test Fluid)	8.0 to 11.0
Precipitated Matter, % vol (Max)	0.05
Simulated Service: Metal Pit Etch & Galling	Slight
232,500 stroking cycles Piston or Cyl Dia chg (in.)	≤0.005
Temp -67° to +158°F Rubber Cup Dia chg (in.)	≤+0.035
Rubber Cup Lip Interference, %	≤65
Rubber Hardness chg (durometer)	
Points	≤10.0
Rubber Cup Swell, Scuffing, Crack, etc.	Moderate
Max Pressure chg in 12 hr period, psi	+35 to -50
Fluid, Vol Loss 24 hr (ml/1,000 Strokes)	≤1.5
Fluid Leakage; 100 cycles at 500 psi; ml (Max)	36.0
Fluid Sediment, % vol (Max)	1.0
Compatibility:	All Spec. Fluids

(cont'd next page)

MIL-H-13910B: HYDRAULIC FLUID, POLAR-TYPE AUTOMOTIVE BRAKE, ALL WEATHER (cont'd)	
PROPERTIES	VALUES
Stability: 72 hr at 77°F and 168 hr at 158°F Max wt Loss, mg/cm ² NATO Symbol: Recommended Operating Temp Range, °F: Foaming: Storage Stability:	Aluminum Alloy Cast Iron Pit or Etch Gum Deposit 0.05 0.3 Moderate Moderate None -67 to +131 -- NR
Notes: NR, no requirements. --, no information. Use: Automotive hydraulic brake systems. Not recommended as preservative fluid for storage.	

VV-B-680a: BRAKE FLUID, AUTOMOTIVE	
PROPERTIES	VALUES
Color:	NR; Transparent
Specific Gravity:	NR
Pour Point, °F (Max):	<-58
Boiling Point, °F (Min):	374
Boiling Point Change, °F (Max):	±5.4
Boiling Point Compatibility, °F (Max):	±9.0
Flash Point, °F (Min):	179.6
Viscosity, cSt: -31°F (Max)	900
122°F (Min)	3.5
212°F (Min)	1.3
pH Value: (fluid-water-alcohol mixture)	7.0 to 11.0
Evaporation: (7 days at 212°F cycle), % wt Loss (Max)	80
Residue, Quality	Fluid & Oily
Precipitated Matter	Slight; Non-gritty
Residue Properties, Pour Point, °F (Max)	<23
Viscosity, cSt: 32°F (Max)	7,000
122°F (Min)	35
212°F (Min)	10
Low Temp Properties: Appearance	Transparent
6 hr at -58°F, Bubble Rise Time, sec (Max)	35
2 hr at -40°F, Bubble Rise Time, sec (Max)	10
Fluid-Water Mixture: 24 hr at -40°F, Bubble Rise, sec (Max)	10
24 hr at 140°F, appearance	No Stratification
Rubber Swell: (120 hr at 158°F), Cup dia increase (in.)	0.006 to 0.050
Durometer chg, at 158°F, points	≤-10 to +0
Durometer chg, at 248°F, points	≤-10 to +0
Rubber Condition	No Disintegration
Corrosiveness: Tinned Iron	0.2
120 hr at 212°F Carbon Steel	0.2
Max wt chg, mg/cm ² Aluminum Alloy	0.1
Cast Iron	0.2
Brass	0.4
Copper	0.4
Pit or Etch of Metal Strips	None
Rubber Cup Condition	No Disintegration
Max Cup dia increase, in.	0.05
Rubber Hardness chg (durometer) Points	<-15
pH Value (Test Fluid)	7.0 to 11.0
Precipitated Matter, % vol (Max)	0.05
Simulated Service Test: Metal Pit., Etch. or Galling	None
300,000 Stroke Cycles Piston or Cyl. dia chg (in.)	≤0.005
Temp from 77° to 248°F Rubber Cup dia chg (in.)	≤+0.035
Pressure 500-1,000 psi Cup Lip Intef., %	≤65.0
Rubber Cup Durometer chg (Points)	≤15.0
Rubber Cup Swell, Scoring, Crack, etc.	Moderate
Max Pressure chg in 12 hr, psi	+35 to -50
Fluid Loss in 24,000 cycles, ml (Max)	36.0
(cont'd next page) Fluid Sediment, % vol (Max)	1.5

VV-B-680a: BRAKE FLUID, AUTOMOTIVE (cont'd)	
PROPERTIES	VALUES
Compatibility: Stability: Aluminum Alloy 72 hr at 77°F and 168 hr Cast Iron at 158°F, Max wt Loss, Metal Pit or Etch mg/cm ² Gum Deposit NATO Symbol: Military Symbol: Recommended Ambient Temp Range, °F : Recommended Fluid Temp Range, °F : Foaming: Storage Stability:	All Spec. Fluids 0.05 0.3 None None H-542 HB -31 to 131 -31 to 374 -- NR
Notes: NR, no requirements. --, no information. Use: Operating hydraulic fluid for automotive brake systems and similar systems. Not recommended for storage or stationary systems.	

MIL-H-22072A(WP): HYDRAULIC FLUID, CATAPULT	
PROPERTIES	VALUES
Color:	Red
Specific Gravity: 68°F	1.04 to 1.06
Pour Point, °F (Max):	NR
Flash Point, °F (Min):	NR
Cloud Point, °F (Min):	210
Compression Ignition: 140°F at 4,000 psi	None
Viscosity, cSt: 0°F (Max)	1,760
100°F	40.72 to 45.0
130°F (Min)	21.7
Evaporation: 4 hr at 158°F	Not Hard or Resinous
Volatility: 30 min at 70-80°F, % wt Loss (Max)	10.0
Composition:	Not Limited (Fire Resist.)
Water Content, % wt	50 ± 1.5
Lubricity Additive, % wt	Permitted
Corrosion Inhibitor, % wt	Permitted
Viscosity-Temperature Improver, % wt	Permitted
Foaming: 5 min blowing at 75°F, ml (Max)	No Limit - Report
10 min settling at 75°F, ml (Max)	10.0
pH Value:(fluid-water mixture)	8.8 to 9.2
High Temp Stability: 168 hr at 158°F	No Chemical Change
Low Temp Stability: 6 hr at 10°F	No Crystallization
Effect on Packings: O-Ring, 168 hr at 158°F; % vol chg	-5.0 to +10.0
Effect on Other Elastomerics: Std. Cond.	Negligible
Corrosion (Static): Steel	0.4
720 hr at 158°F Naval Brass	0.4
Max wt Loss, mg/cm ² Manganese Bronze	0.4
Copper	0.4
Pit or Etch (Max)	Slight
Fluid Color chg	None
Separation or Sludge	None
Corrosion (Stirring): Steel	0.7
336 hr at 158°F Copper	0.7
Max wt Loss, mg/cm ² Pit or Etch (Max)	Slight
Fluid Color chg	None
Separation or Sludge	None
Storage Stability: 12 month at 77°F	Satisfactory
Pump Test: 500 hr, Mod. Vickers	Satisfactory
Compatibility:	All Spec. Fluids
Toxicity:	No Special Handling
NATO Symbol:	None
Recommended Ambient Temp Range, °F:	--
Notes: NR, no requirements. --, no information. Report, no limits, but report data. Use: Fire resistant fluid for power transmission for hydraulic systems such as aircraft catapults.	

d. *Uses:* A fire resistant water base liquid intended as a power transmission media for hydraulically actuated systems such as catapults for launching Naval aircraft.

e. *Limitations:* Not recommended for either low or high temperature applications. Liquid will soften most commonly used paints. No special handling procedure is required.

f. *Custodian:* Navy-WP

4-7 VISCOSITY-TEMPERATURE GRAPHS

The pages which follow present ASTM Viscosity-Temperature graphs of the hydraulic fluids discussed in the preceding paragraphs. Where possible, data of typical liquids produced by various manufacturers were

used to generate the graphs. These graphs are included in Figs. 4-1 through 4-10. When manufacturers' data were not available, the graphs show the specification requirements. These graphs are included in Figs. 4-11 through 4-13.

Liquids not identified with a chemical designation are petroleum or petroleum-base liquids.

Graphs of the following liquids are not included because commercial data were not available and/or specification requirements were not sufficient to plot a curve (i.e., viscosity was limited at only one temperature or the specification was for a family of liquids of various viscosities):

MIL-H-46001A
MIL-L-17331D
VV-D-001078
MIL-H-5559A
MIL-P-46046A
JAN-F-461

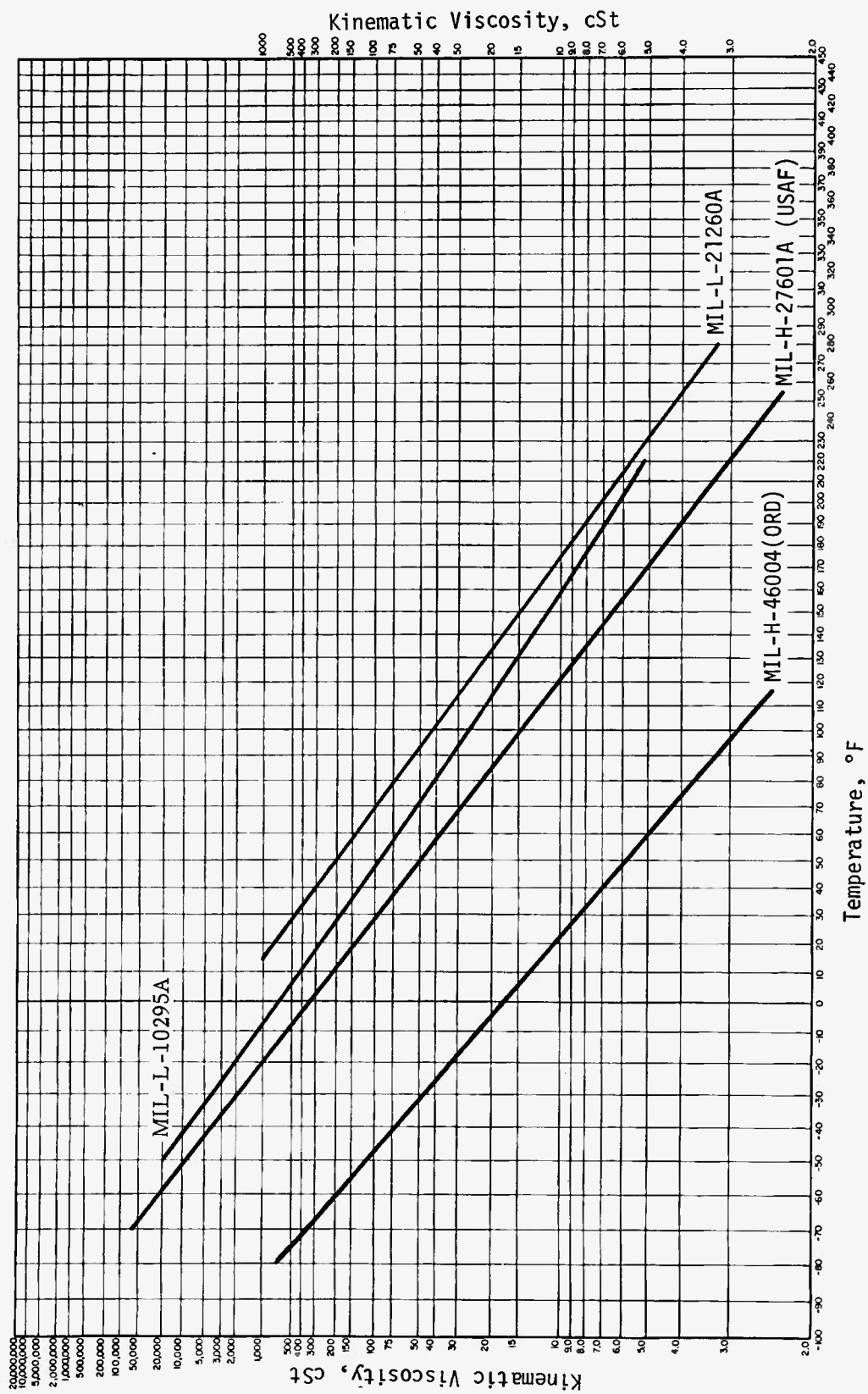


Fig. 4-1. Viscosity-temperature Graphs of Specification Liquids MIL-L-10295A, MIL-L-21260A, MIL-H-27601A(USAF), and MIL-H-46004(ORD)

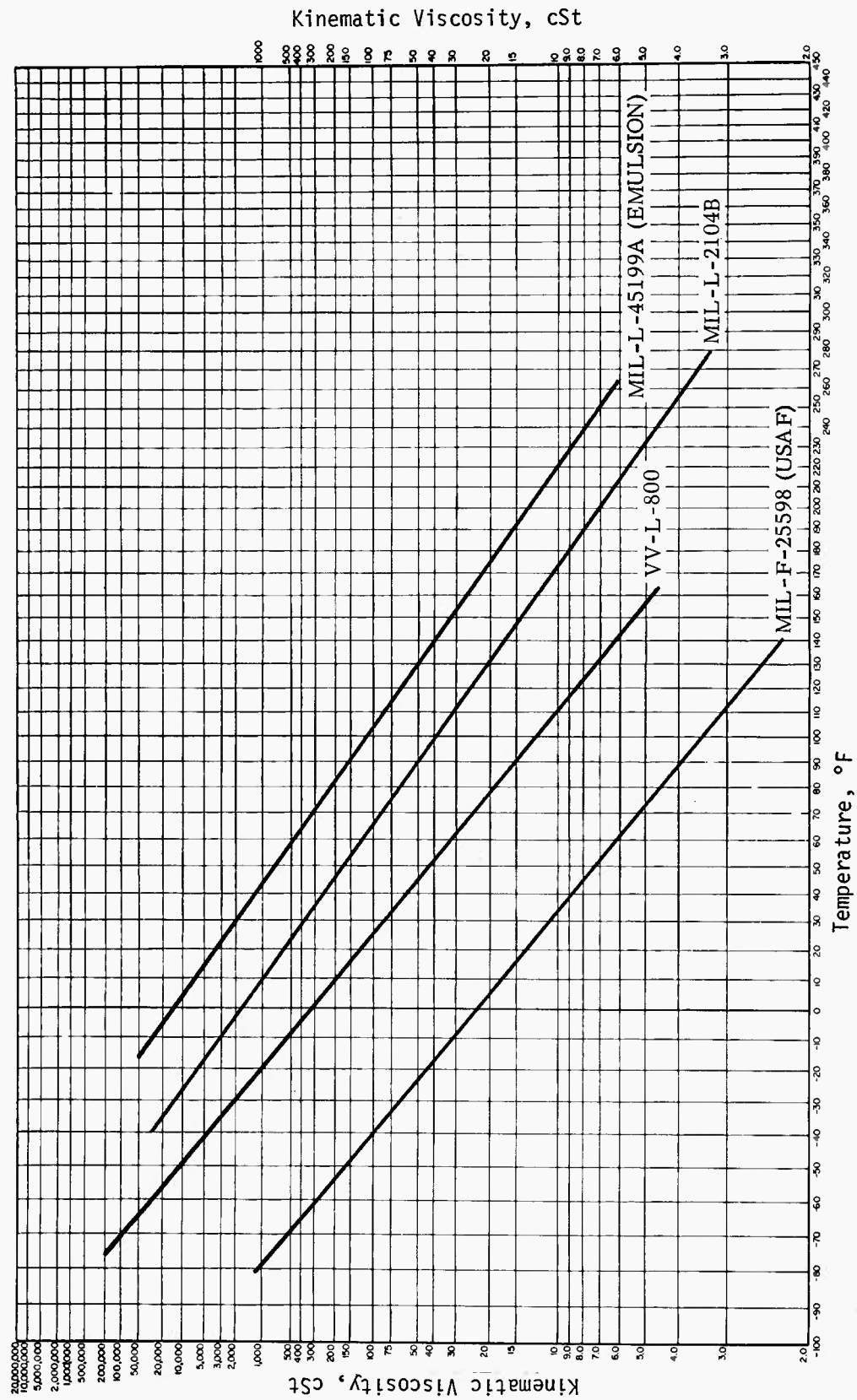


Fig. 4-2. Viscosity-temperature Graphs of Specification Liquids VV-L-800, MIL-L-2104B, MIL-F-25598(USAF), and MIL-L-45199A

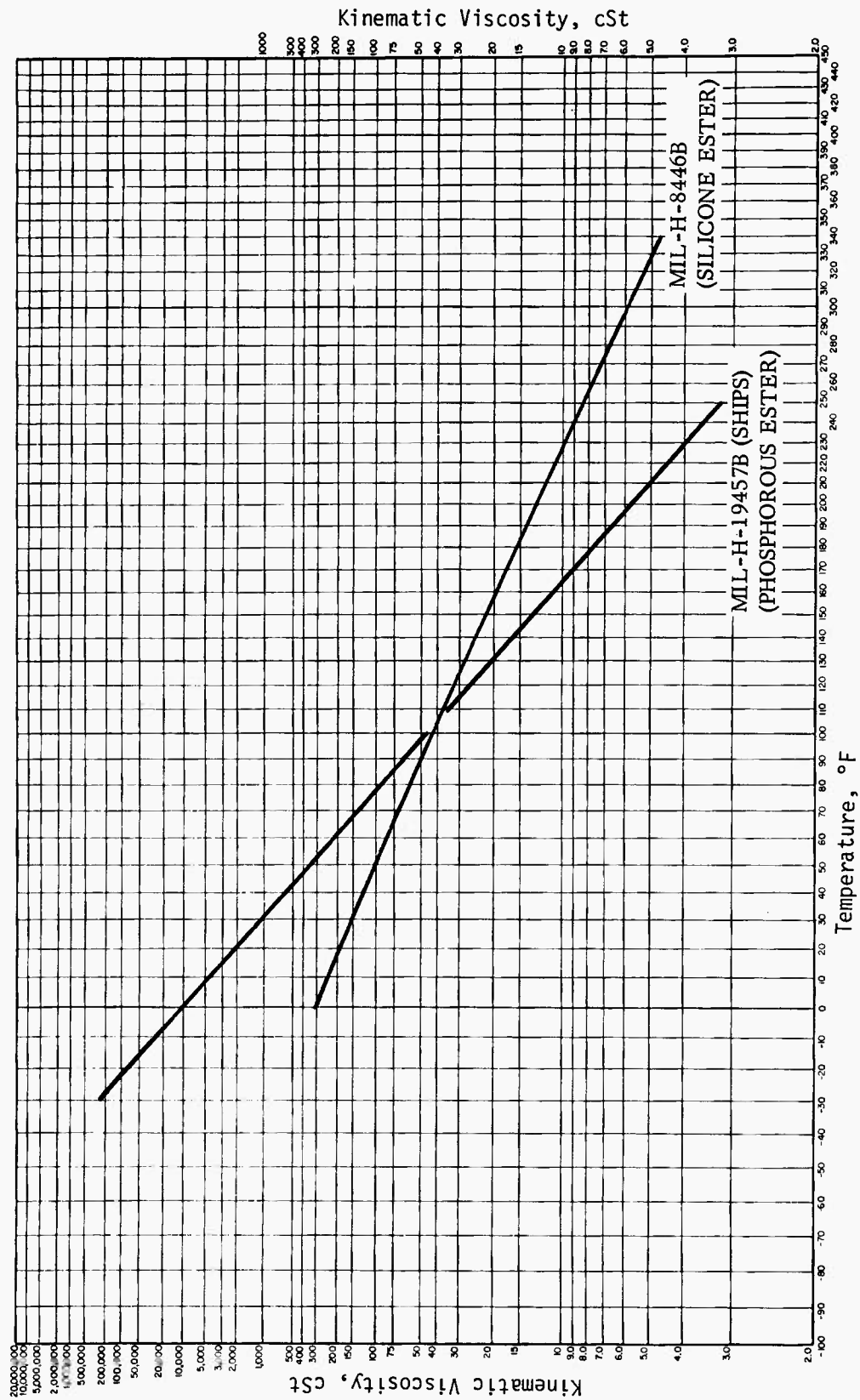


Fig. 4-3. Viscosity-temperature Graphs of Specification Liquids MIL-H-8446B and MIL-H-19457B(SHIPS)

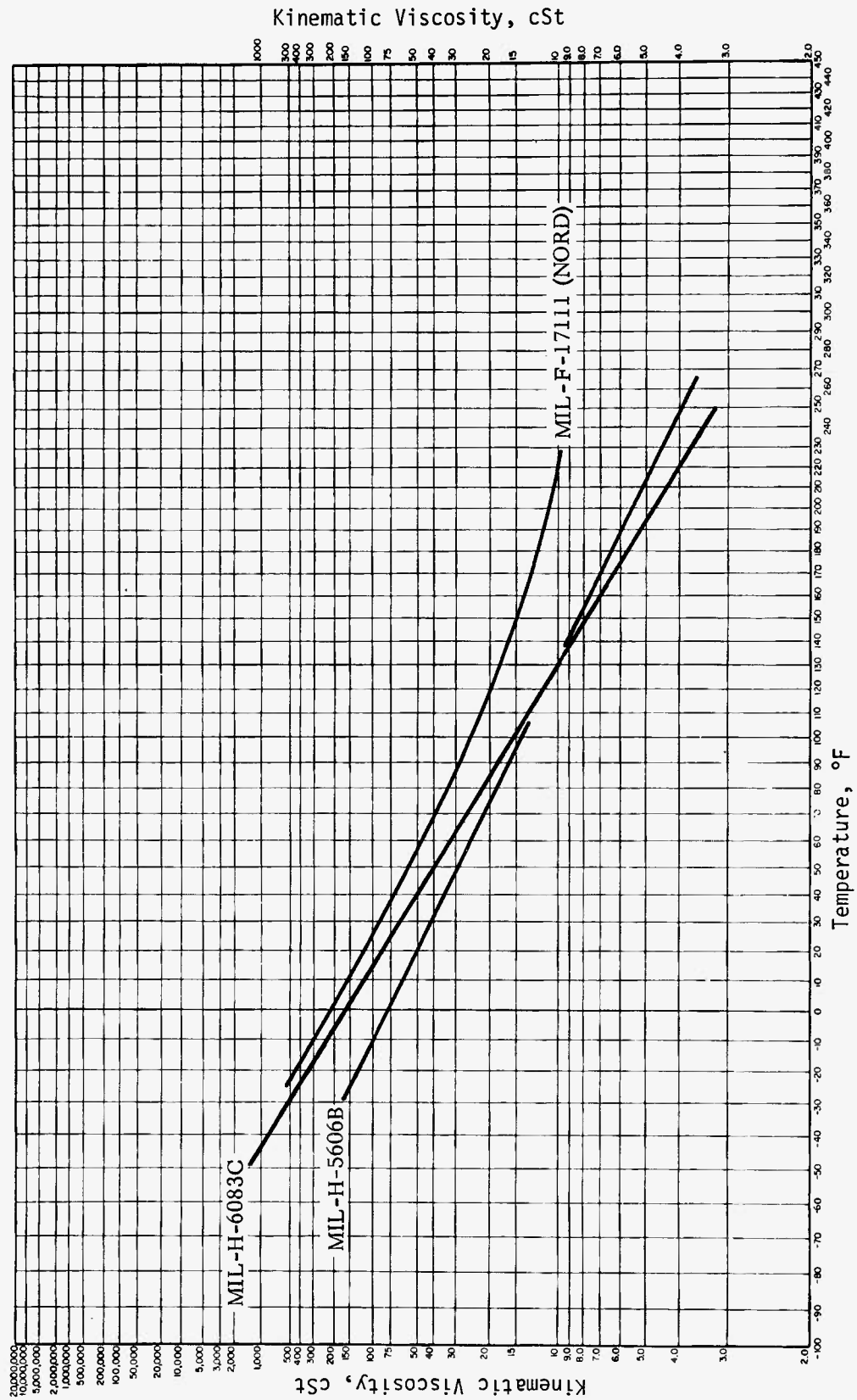


Fig. 4-4. Viscosity-temperature Graphs of Specification Liquids MIL-H-5606B, MIL-H-6083C, and MIL-F-17111(NORD)

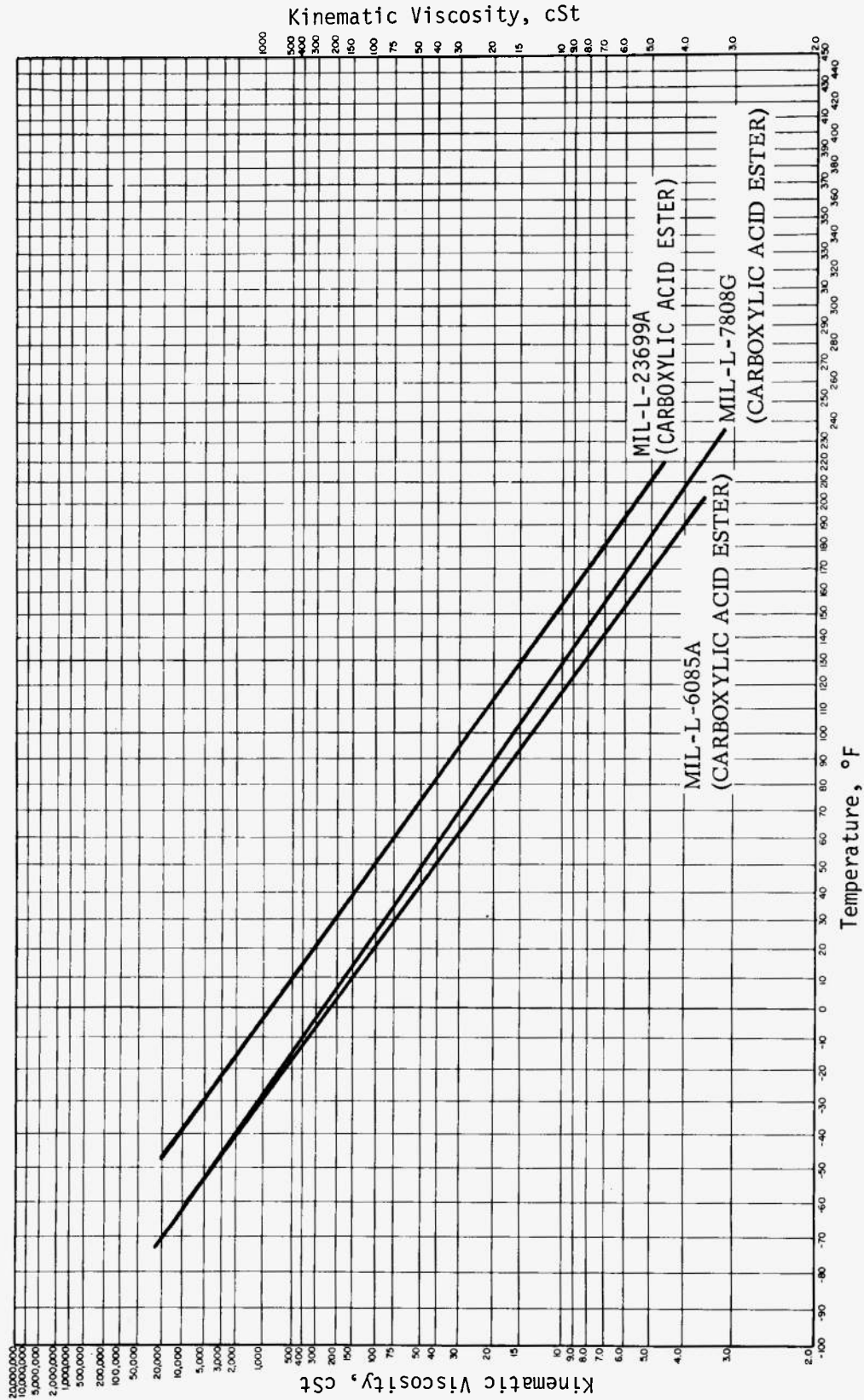


Fig. 4-5 . Viscosity-temperature Graphs of Specification Liquids MIL-L-6085A, MIL-L-7808G, and MIL-L-23699A

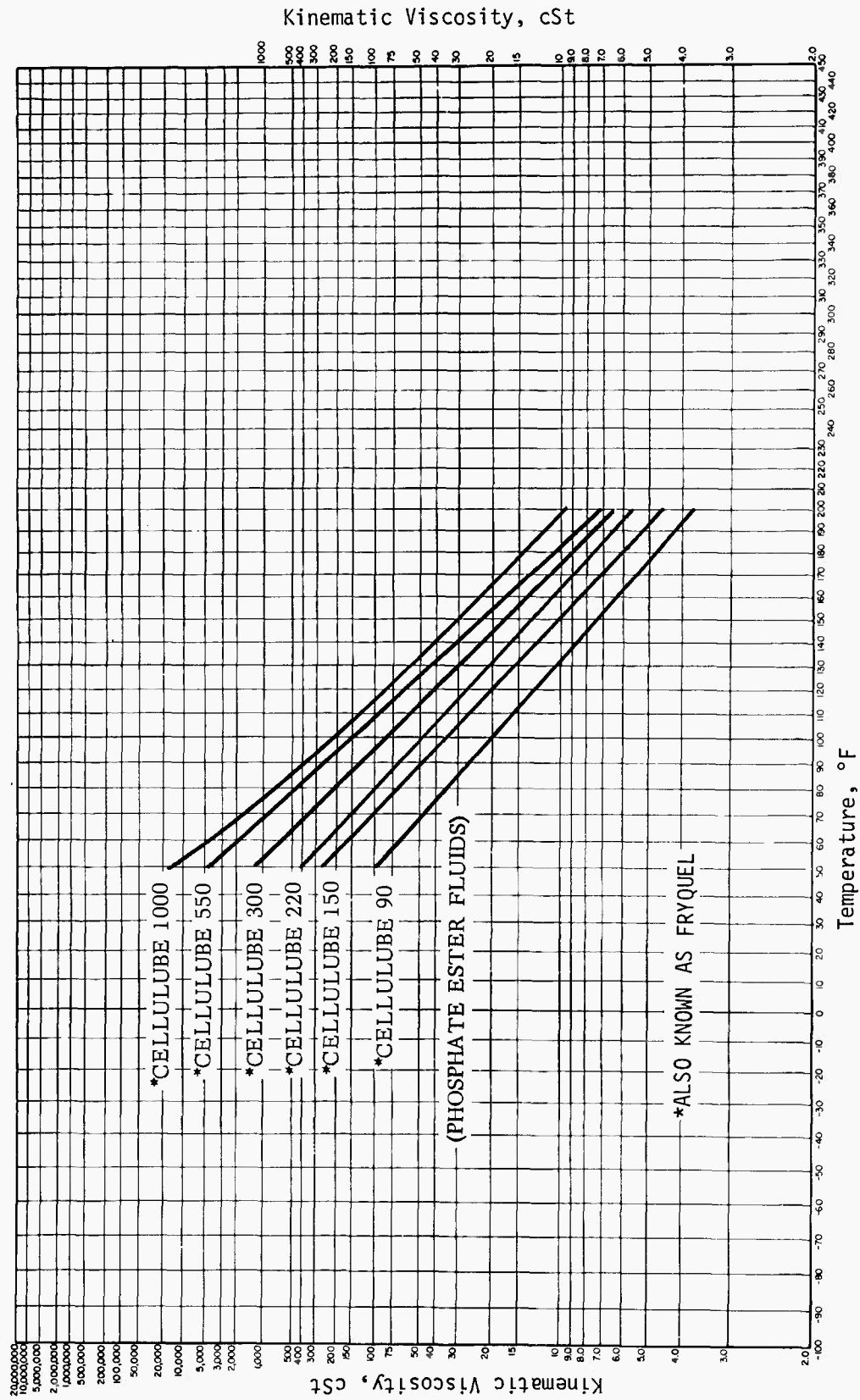


Fig. 4-6. Viscosity-temperature Graphs of Commercial Phosphate Ester Liquids

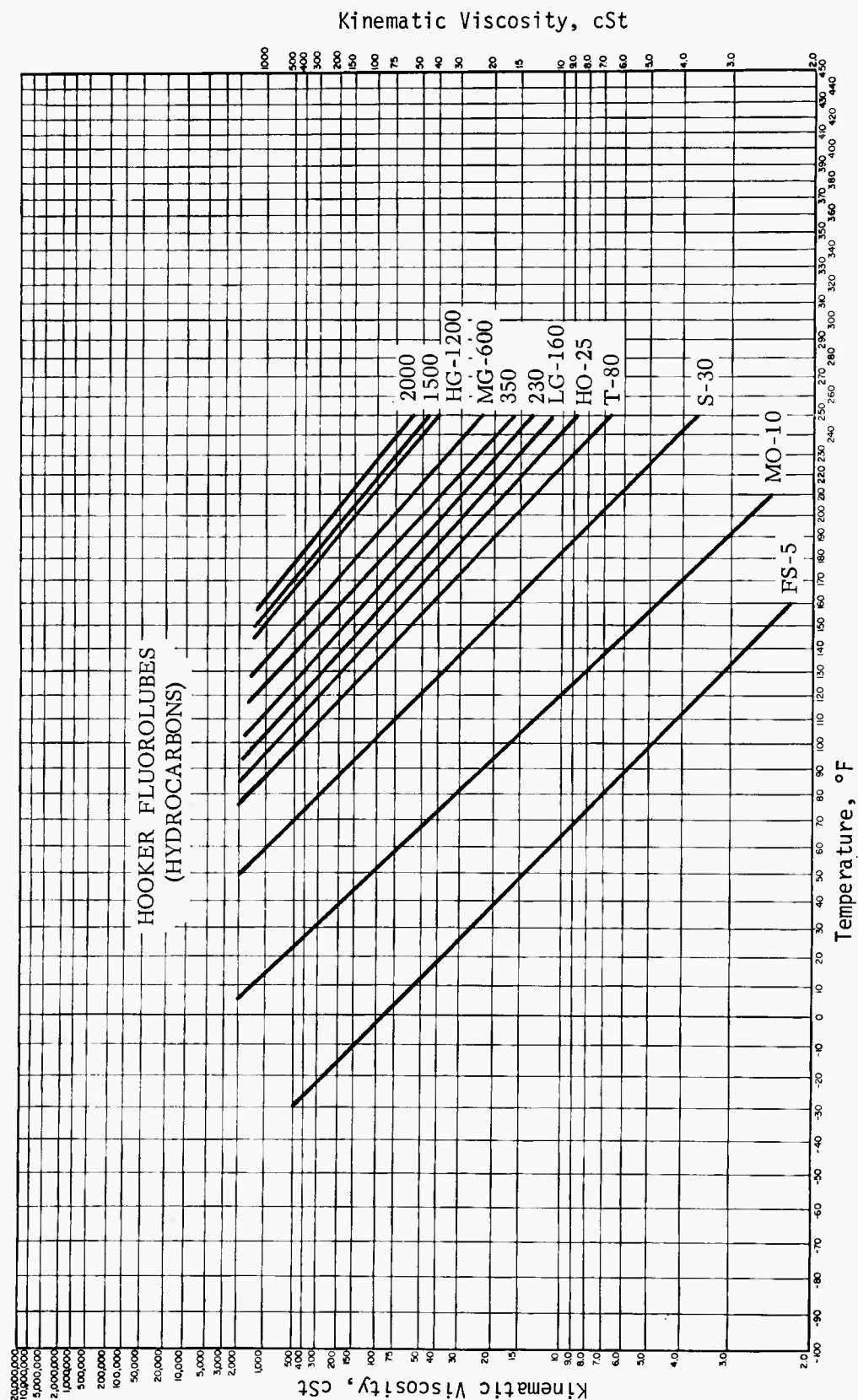


Fig. 4-7. Viscosity-temperature Graphs of Commercial Hydrocarbon Liquids

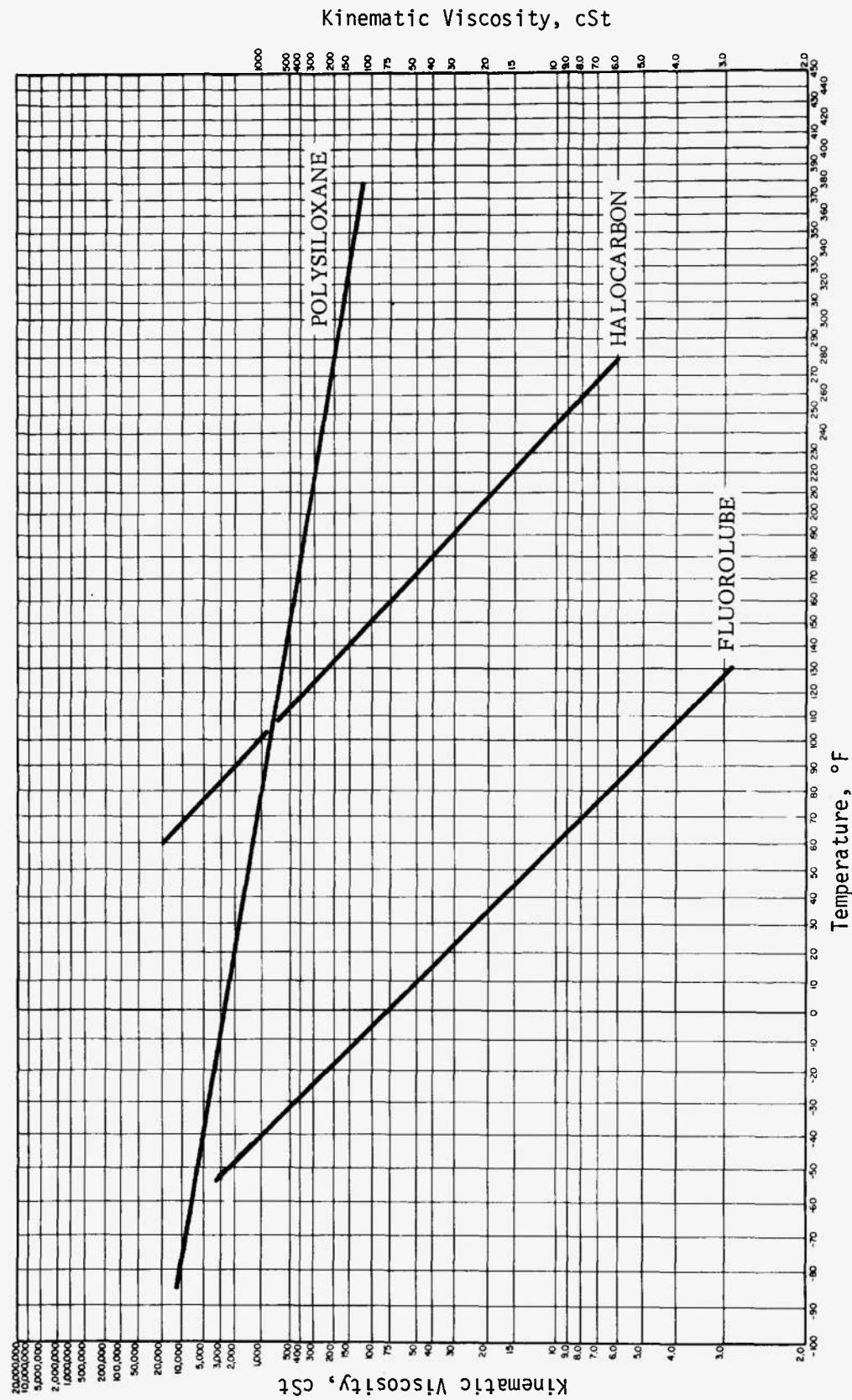


Fig. 4-8. Viscosity-temperature Graphs of Commercial Polysiloxane, Halocarbon, and Fluorolube Liquids

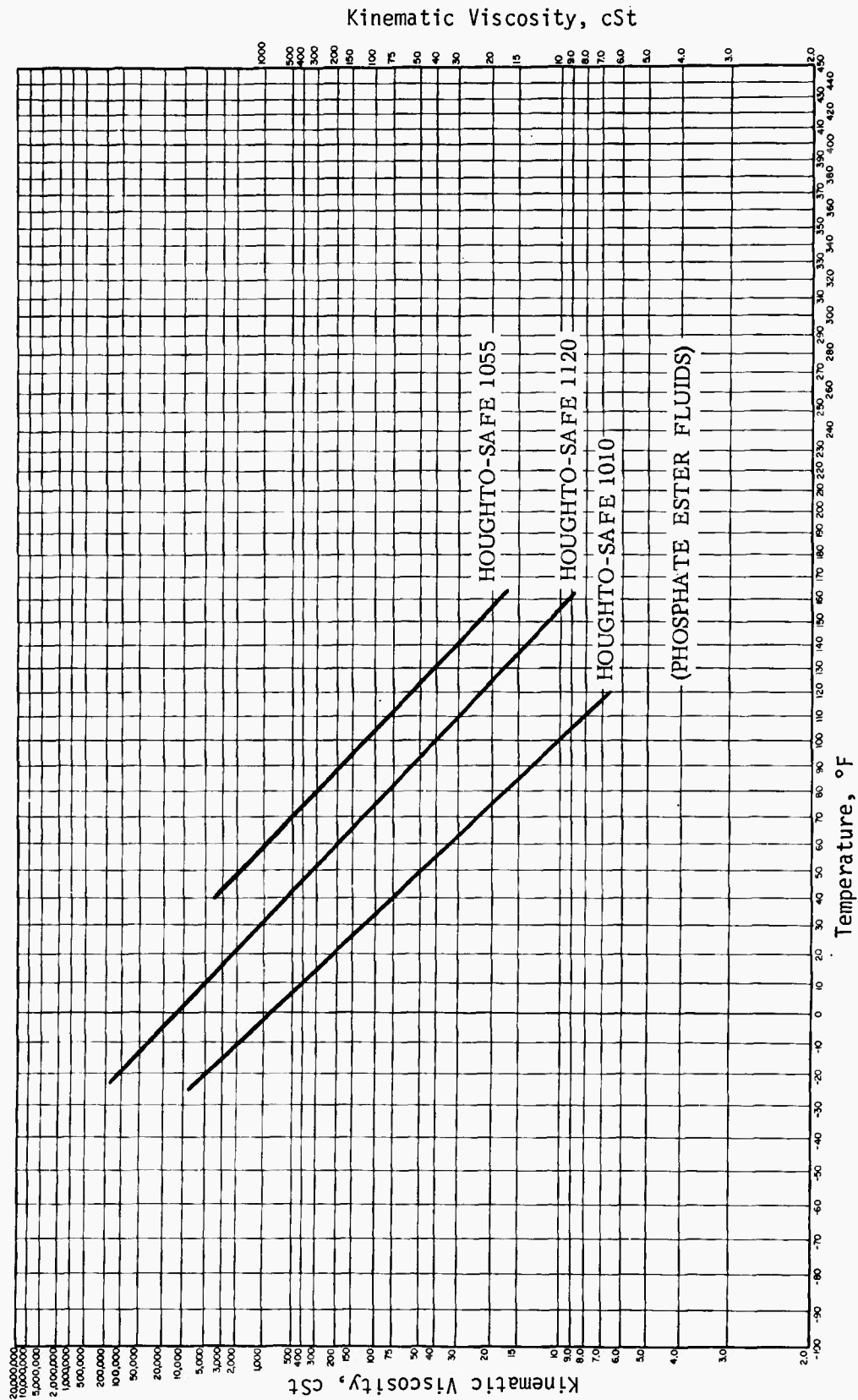


Fig. 4-9. Viscosity-temperature Graphs of Commercial Phosphate Ester Liquids

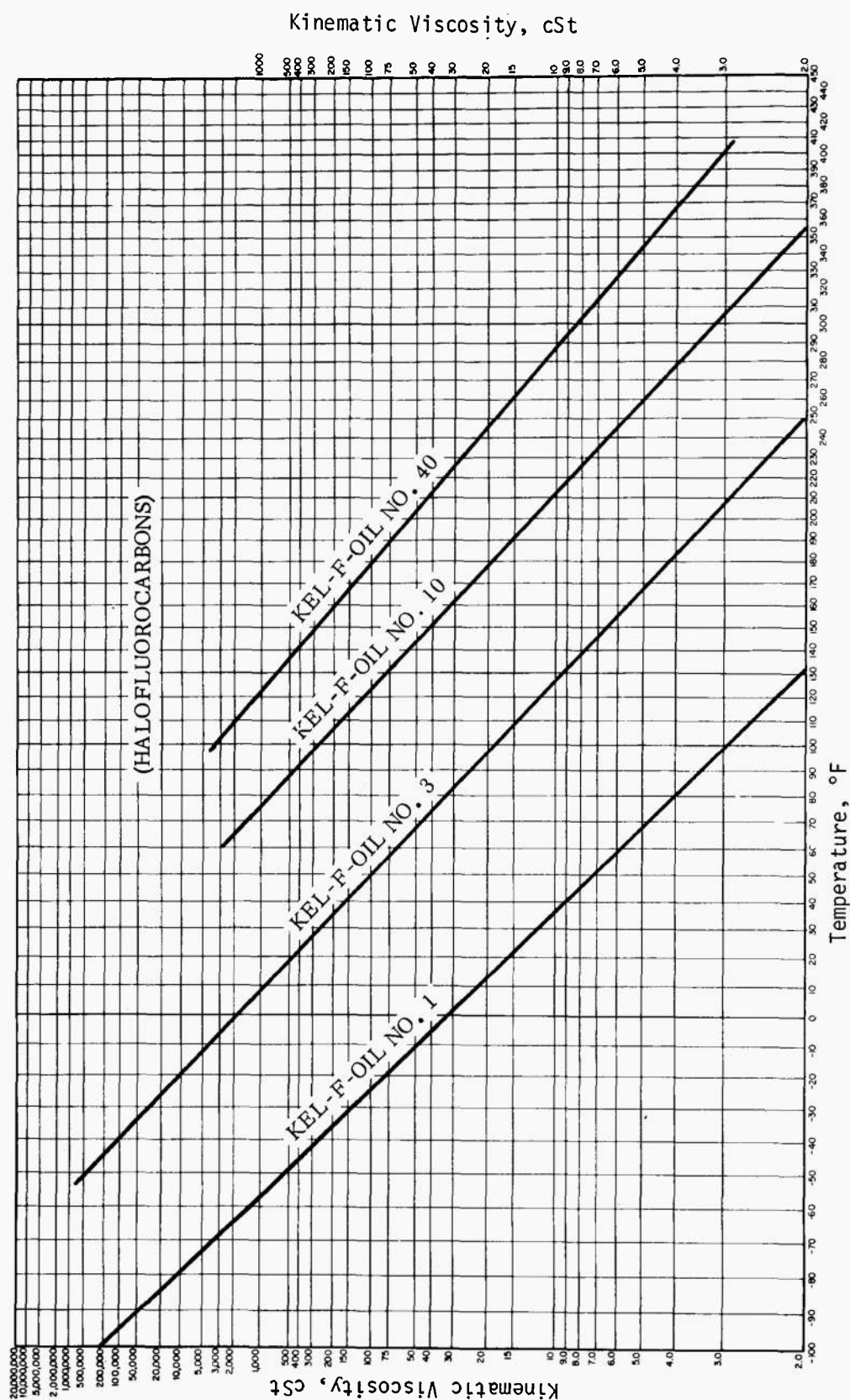


Fig. 4-10. Viscosity-temperature Graphs of Commercial Halofluorocarbon Liquids

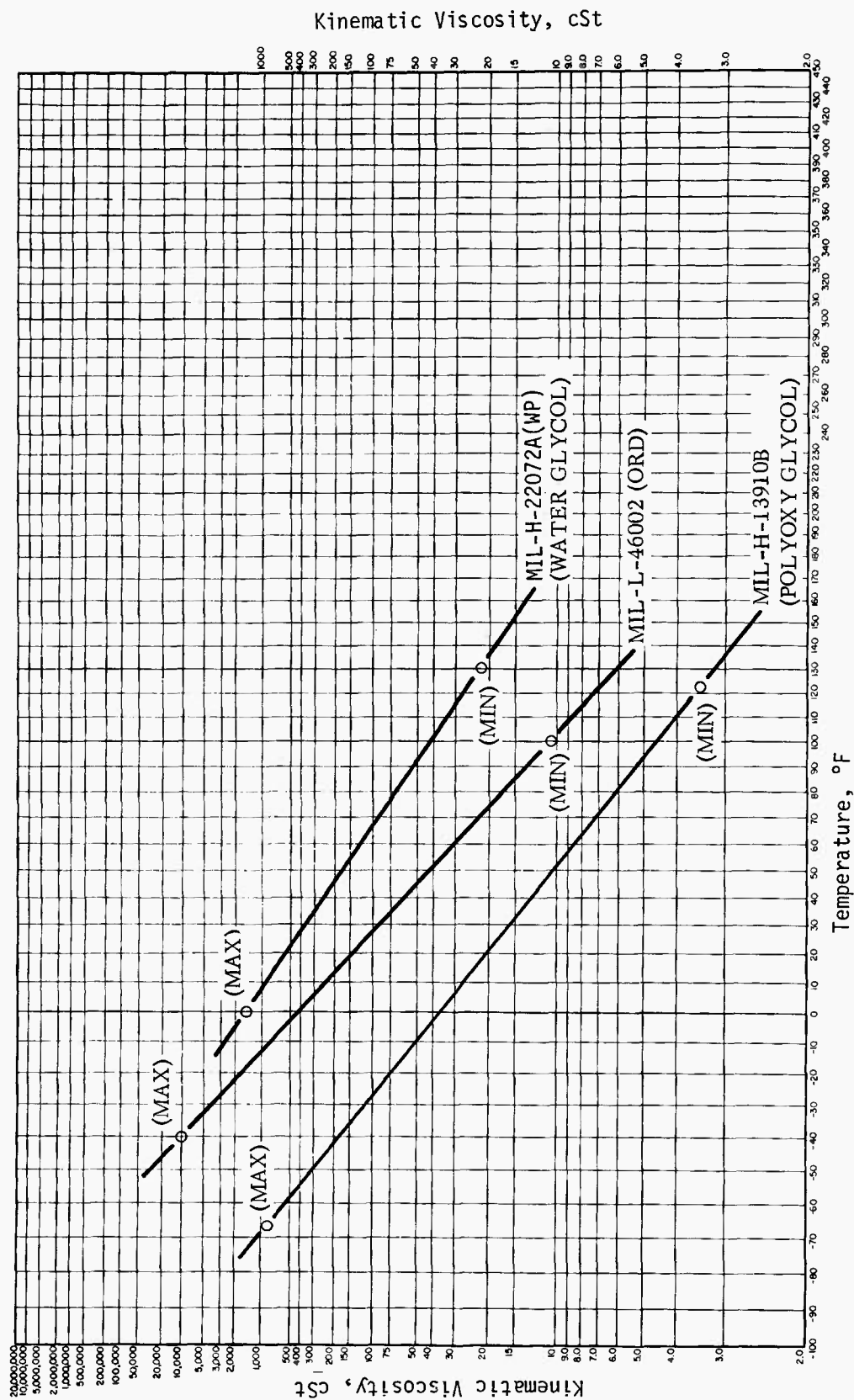


Fig. 4-11. Viscosity-temperature Graphs of Specification Requirements for MIL-H-13910B, MIL-H-22072A(WP), and MIL-L-46002(ORD)

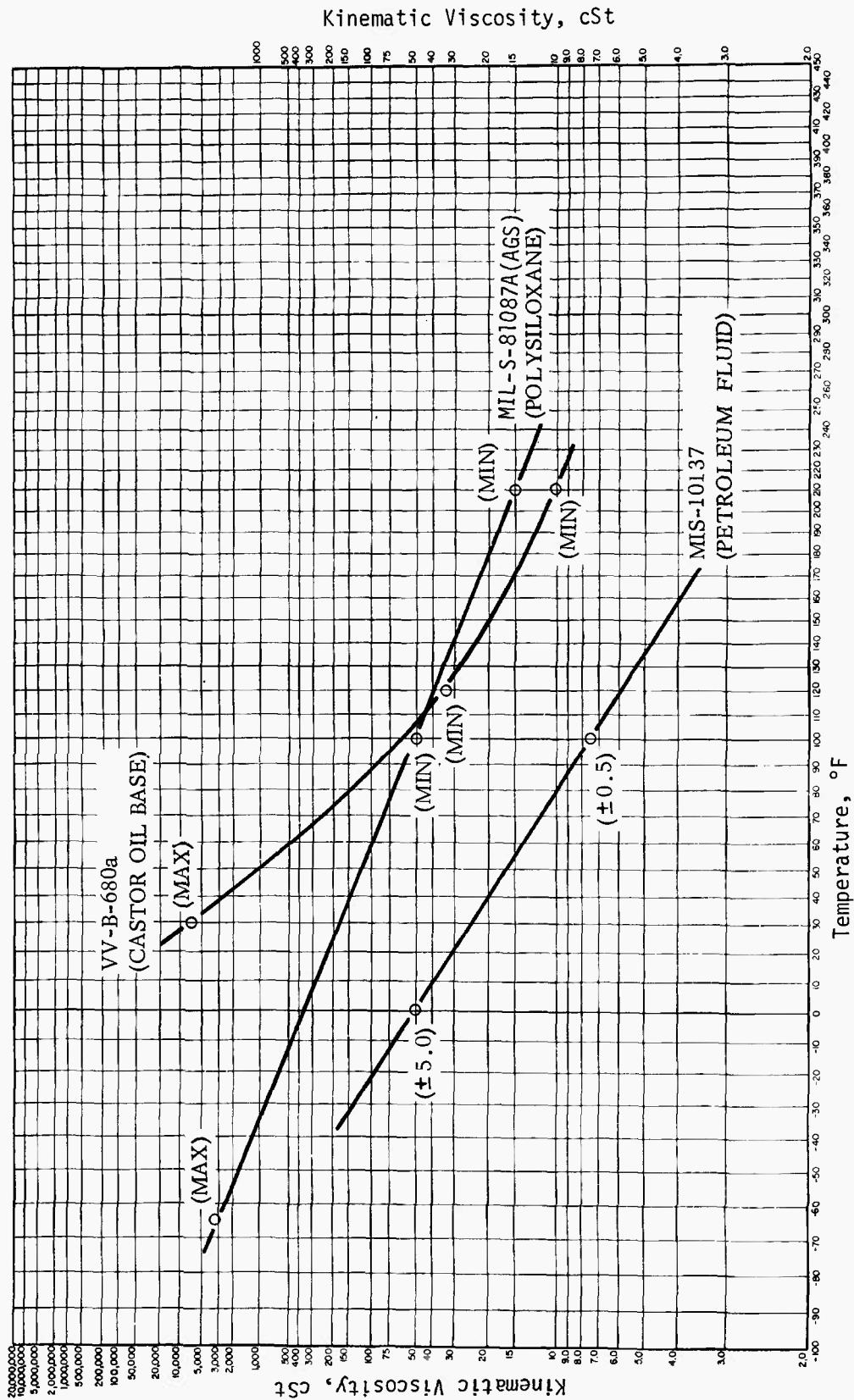


Fig. 4-12. Viscosity-temperature Graphs of Specification Requirements for VV-B-680a, MIS-10137, and MIL-S-81087A(AGS)

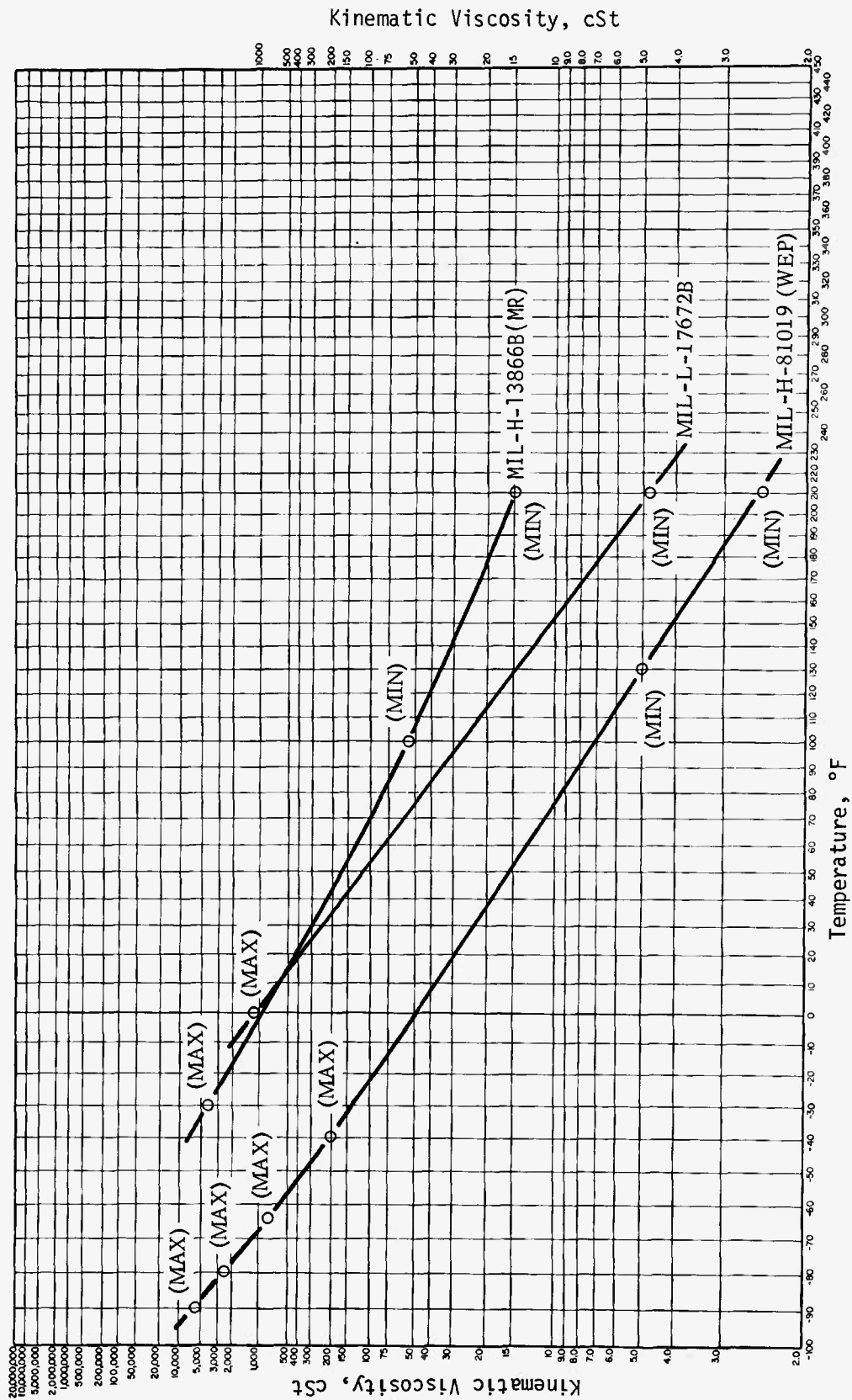


Fig. 4-13. Viscosity-temperature Graphs of Specification Requirements for
MIL-H-13866B(MR), MIL-L-17672B, and MIL-H-81019(WEP)

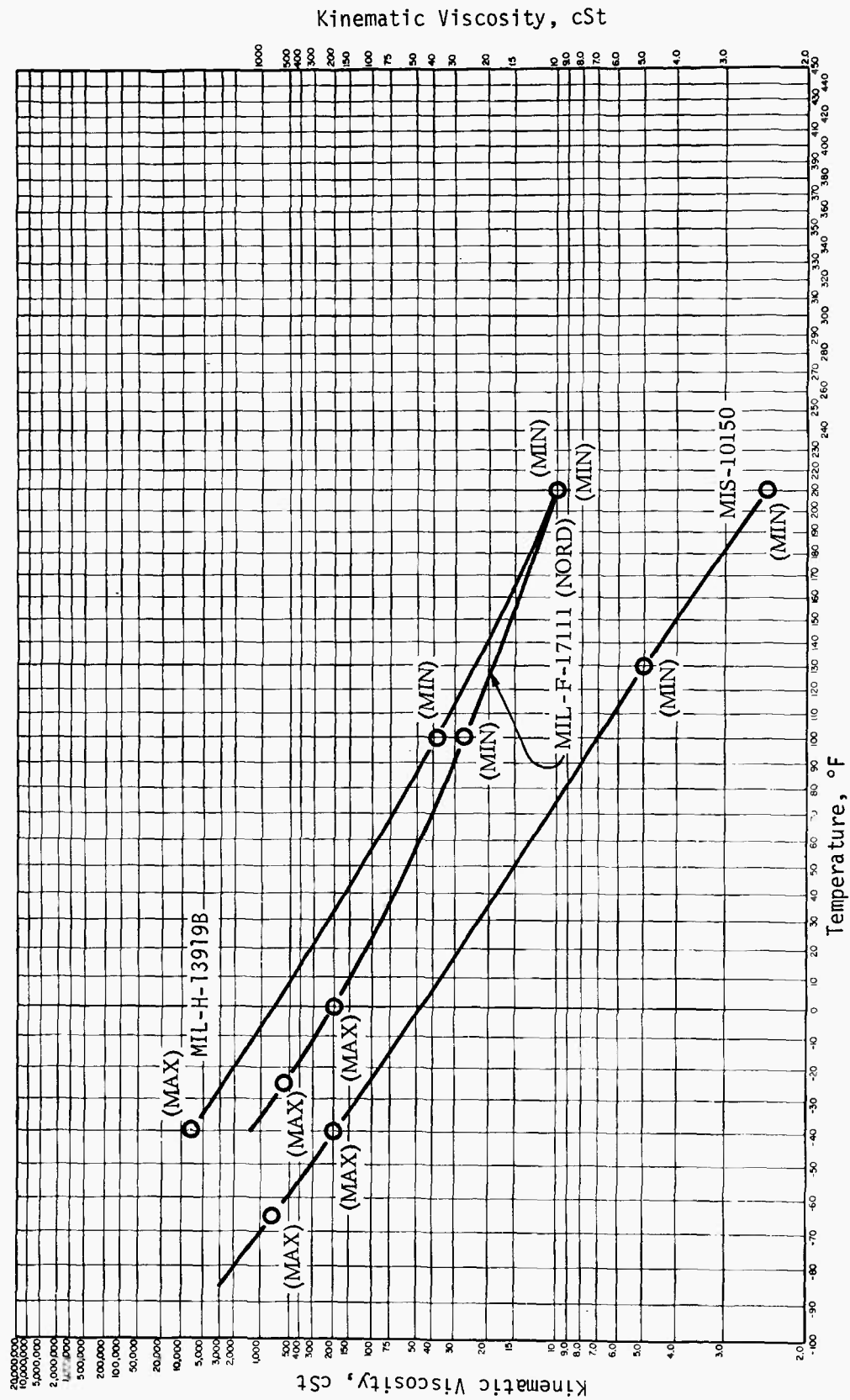


Fig. 4-14. Viscosity-temperature Graphs of Specification Requirements for MIL-H-13919B, MIL-F-17111(NORD), and MIS-10150

CHAPTER 5

ADDITIVES

5-1 GENERAL

Formally defined, an additive for hydraulic fluids and lubricants is a compound or component that enhances some property of, or imparts some new property to, the base fluid. A base stock hydraulic fluid that cannot meet requirements for operation in a given hydraulic system frequently can be modified through the use of additives in such a way that the range of satisfactory operation of the base liquid can be extended to meet more severe requirements. In the formulation of a hydraulic fluid, additive components may constitute from less than one to as much as 20 percent of the final liquid composition. The more important classes of additives include oxidation inhibitors, corrosion inhibitors, viscosity index improvers, foam inhibitors, and lubricity additives.

In the selection of additives and formulation of a fluid, each additive must be compatible with the base stock, other additives, and system components. Examples of problems of compatibility that can be encountered are cited throughout this chapter. Solubility of additives in the base stock is an important limitation in the use of some additives at low temperatures.

Although general theories can be developed for the mode of action of different kinds of additives, an effective additive in one hydraulic fluid may not be equally effective in another. The range of conditions that a hydraulic fluid may encounter during storage and use will determine the selection of additives. Therefore, the formulation of a hydraulic fluid must take into account a wide variety of factors, and the effectiveness of each additive must be verified experimentally. Several of the common hydraulic fluid shortcomings, and the technology and additives developed to compensate for them are discussed in the remainder of this chapter.

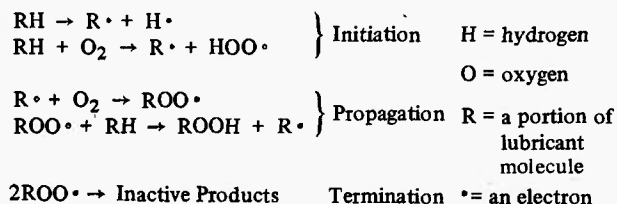
5-2 OXIDATION INHIBITORS

In environments that contain even small amounts of oxygen, the oxidation stability of a hydraulic fluid

limits its useful life as well as its upper temperature limitation. Therefore, additives or inhibitors that increase the resistance of the fluid to the chemical changes associated with oxidation are very important. Ultimate changes that may be encountered as a result of oxidative deterioration include changes in viscosity; the precipitation of insolubles, including lacquers and varnish; and an increase in acidity and corrosiveness. In a consideration of the oxidative stability of a hydraulic fluid, accompanying corrosion effects should not, and usually are not, be considered independent of oxidation. For this reason, laboratory screening of oxidation inhibitors usually also considers changes in acidity of the hydraulic fluid and the corrosion of metal samples in contact with the fluid.

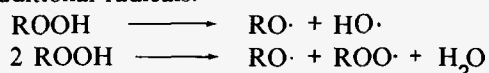
5-2.1 MODE OF ACTION OF ANTIOXIDANTS

In order to properly consider the mode of action of antioxidants, some knowledge of the mechanism of oxidative degradation is necessary. Liquid phase oxidation is considered a free radical process undergoing the usual steps of initiation, propagation, and termination. Schematically, after the process has been initiated, the course of oxidation in petroleum oils can be represented as follows:



Initiation reactions in lubricants are most often thermally activated but may also be induced by light, ionizing radiation, or other means. Since the propagating species ($\text{R}\cdot$) can be continuously regenerated, the process is a chain reaction. Termination occurs with the formation of nonradicals such as alcohols, aldehydes, ketones, and olefins, which are also susceptible to oxidation and may produce acids, sludge,

and varnish. At elevated temperatures, the intermediate hydroperoxide can decompose and produce additional radicals:



Since the concentration of radicals present can increase with time, oxidation is autocatalytic. Also, when acidic materials are formed in a hydraulic fluid which is in contact with metals as a consequence of oxidation, metal corrosion can occur with the formation of metal ions, which can become soluble in the fluid. These metal ions—particularly those of iron, lead, and copper—are catalysts in the oxidation process. The stable shelf life under oxidative conditions of di-2-ethylhexyl sebacate at 347°F (175°C) in the presence of various metals illustrates this catalytic effect: no catalyst, 125 hr; copper, 20 hr; copper-beryllium, 30 hr; steel, 115 hr; and aluminum, 120 hr (Ref. 1).

Although metal ions are pro-oxidants at lower temperatures in hydrocarbon liquids, they can function as antioxidants in higher temperature fluids such as silicones, phenyl ethers, and fluoroesters (Ref. 2). At higher temperatures in these fluids, the metal ions presumably alter the course of the hydroperoxide reactions and produce nonradical products.

5-2.2 CLASSES OF ANTIOXIDANTS AND SYNERGISM

Antioxidants are effective in one of three ways—(1) metal deactivators minimize the catalytic effect of trace amounts of metal ions in the fluid; (2) free radical acceptors break the chain reaction in the propagation step; and (3) hydroperoxide destroyers inhibit the formation of free radicals in the hydroperoxide decompositions. A combination of antioxidants that may serve several of these purposes may be used.

5-2.2.1 Metal Deactivators

The metal deactivators most commonly used are sequestering or chelating agents. These include N,N'-disalicylidene diamine, mercaptothiadiazole, quinizarin, and alizarin.

5-2.2.2 Free Radical Acceptors

Amines and phenols are most commonly used as free radical acceptors and are effective in many base stocks.

Hindered phenols—such as 2,6-ditertiary-butyl-4-methylphenol and aromatic amines such as phenyl-1-naphthylamine—are very effective.

5-2.2.3 Hydroperoxide Destroyers

A variety of sulfur, selenium, and phosphorus-containing compounds can function as hydroperoxide destroyers. Effective materials include phenothiazine, phosphorus pentasulfide-olefin reaction products, zinc dialkyldithiophosphates, sulfurized olefins, alkyl polysulfides, dialkylphosphonates, trialkyl phosphites, zinc dialkyl dithiocarbamates, alkyl trithiocarbamates, and alkyl selenides. Phenothiazine is particularly useful at higher temperatures.

5-2.2.4 Synergism

The combined effect of two or more inhibitors is often greater than the sum of the effects of the individual inhibitors. This synergistic effect has led to the common practice of employing two or more oxidation inhibitors. Not only can synergism occur through the reinforcement of inhibitors through their effectiveness in different phases of the oxidation mechanism, but also by the second inhibitor regenerating the first. For example, synergistic effects observed at 150°C when dialkyl phosphonates are used with sterically hindered alkyl phenols are attributed to the phosphonates transferring hydrogen to the oxidized phenols (Ref. 3).

5-2.3 EXAMPLES OF THE USE OF INHIBITORS IN VARIOUS FLUID LUBRICANTS

The effectiveness of various classes of materials as oxidation inhibitors in different kinds of hydraulic fluids and certain problems attendant with their use can be illustrated by the results of recent research. Since oxidation rates increase rapidly with temperature, inhibitors useful at higher temperature have received considerable attention.

5-2.3.1 Esters

Ester fluids can be inhibited against oxidation to at least 212°F (100°C) with 0.1 to 0.2 percent of the usual phenolic and aromatic amine antioxidants (Ref. 4) which are also commonly used in petroleum oils.

A number of inhibitors have been examined for use with esters at higher temperatures. Phenothiazine and its derivatives are usually effective to 350°F (175°C) but lacquer formation has been observed at 325°F (163°C). Phenyl-1-naphthylamine is the most effective of the aromatic amines and has an upper temperature limit of 325°F (163°C). *n*-alkyl selenides are effective at 325°F (163°C), but the analogous sulfur compounds have an upper temperature limit of 257°F (125°C). Phosphites, which are effective to 212°-257°F (100°-125°C), are limited by their hydrolytic susceptibility and volatility. Except for serious copper corrosion at 325°F (163°C), 4-*tert*-butylphenyl-2-mercaptothiazole provides adequate inhibition. The zinc complex of dibutyldithiocarbamate and dibutylamine functions satisfactorily at 302 °F (150°C) (Ref. 5).

Phenothiazine substantially extends the induction period at 350°-400°F (175°-205°C) and reduces the rate of oxidation at 500°F (375°C). However, at the higher temperature, phenothiazine, as well as other amine inhibitors, causes darkening and the formation of trace dirtiness in the liquids (Ref. 1).

At 425° and 500°F (218° and 260°C), the most effective selenides for inhibiting oxidation are *p*-amino-phenyl phenyl selenide, 5-dimethylaminobenzo(2,1,3) selenadiazole, and diphenyl diselenide. The selenides have been found to be corrosive to copper, silver, magnesium, and aluminum at selenium concentrations of 0.5 percent (Ref. 6).

5-ethyl-10,10-diphenylphenazasiline (5-10-10) is useful in inhibiting ester base stocks at 400°-500°F (205°-260°C). Since a certain thermal level is required to activate 5-10-10 as an antioxidant, it is best used in combination with a low temperature antioxidant. Mixtures of 5-10-10 and phenyl-1-naphthylamine are effective (Ref. 7).

5-2.3.2 Highly Refined Mineral Oils

Natural inhibitors in mineral oils are removed when mineral oils are exhaustively hydrogenated or super-refined, and the oils become even more susceptible to oxidative deterioration. On the other hand, the highly refined mineral oils show a better response to additive modification than the less highly purified oils. Satisfactory inhibitors at 347°F (175°C) are phenothiazine, phenyl-1-naphthylamine, and cadmium diamyldithiocarbamate (Ref. 8).

5-2.3.3 Silicon-containing Fluids

Diarylamines are effective antioxidants in siloxanes at 400°F (205°C) but cause sludging. At that temperature, phenolic antioxidants are ineffective and selenides cause severe copper corrosion. When a sufficiently high degree of nuclear alkylation is introduced into the structure of the diarylamines, sludge formation can be avoided (Ref. 9).

Chlorophenylsilicones have been reported to be adequately stabilized at 500°F (260°C) against oxidation with iron octoate (Ref. 10). Aromatic compounds containing three or more ring systems, for example 1,2-benzanthracene and pyrene, are also effective in retarding the oxidation of a chlorophenylsilicone (Ref. 11). Silane fluids have been found to be not susceptible to improvement with oxidation inhibitors (Ref. 11).

The presence of trace metals can have a profound effect on the oxidative stability of polydimethylsiloxanes and polymethylphenylsiloxanes (Refs. 12, 13). At 392°F (200°C) lead selenium and tellurium accelerate oxidation. Organic selenides, aromatic amines, and phenothiazine prolong the life of silicone oils two to five times, but the life of the oils can be extended to eight times with the use of iron or copper chelates of disalicylaethylenediamine or disalicylalpropylenediamine, the solubilized metal acting as an inhibitor. The use of this inhibitor in poorly ventilated systems under oxygen-deficient conditions, however, leads to the precipitation of the metal as the reduced metal oxide. Cerium complexes have been found not to be subject to this limitation (Ref. 14). New processes have been developed for modifying silicone oils with cerium complexes that raise the stabilization temperature from 617° to 752°F (325° to 400°C) (Ref. 15).

5-2.3.4 Ethers

Tetraphenyltin and bis(*p*-phenoxyphenyl)diphenyltin perform well as antioxidants for poly(phenyl ethers) at 600°-650°F. *p*-bis(triphenylstannoxy)benzene, metal salts of *N,N'*-diphenyldithiocarbamic acid, triphenylbismuth, copper oxides, metal acetylacetonates, metal dithiocarbamates, and the nickel and cobalt chelates of *N*-phenyl-5-nitrosalicylimines were also effective in poly(phenyl ether) systems (Refs. 16-18).

Tris(pentafluorophenyl)phosphine, tris(pentafluorophenyl)-phosphine oxide, tris(4-heptafluorotolyl)phosphine, and tris[4-(pentafluorophenoxy)tetrafluorophenyl]phosphine are effective in eliminating the oxidative deterioration that occurs above 500°F

(260°C) in fluorocarbon polyether liquids but lead to corrosion of ferrous and titanium alloys. Solubility and volatility remain problems in the use of these additives (Refs. 19-21).

5-3 CORROSION INHIBITORS

5-3.1 DEFINITIONS

Corrosion is the deterioration through chemical change of a metal into one or more of its oxides, hydrated oxides, carboxylates, fluorides, carbonates, or other compounds. The special case of the deterioration of iron or steel by moist air (oxygen) is called rusting. Rusting cannot occur in systems from which oxygen is rigorously excluded. Corrosion of metal components in contact with a hydraulic fluid may occur through the action of water and air present in the system, through the action of lubricant decomposition products, or by direct chemical action of the fluid on the metal surface.

A corrosion inhibitor is an additive that prevents or decreases corrosive attack on metals. Although its function may be one of directly protecting the metal surface, an additive may function as a corrosion inhibitor if it interferes with any of the processes that ultimately culminate in corrosion. For this reason, the processes of inhibiting corrosion and oxidation are intimately related.

Not only do oxidation products cause corrosion, but corrosion products may promote oxidation. The interdependence of oxidation and corrosion inhibitors can be illustrated as follows. An antioxidant that retards the auto-oxidation of a fluid will prevent the formation of corrosive acids. Amine antioxidants can react with and neutralize certain acidic materials, but aromatic amines do not effectively neutralize carboxylic acid, a common corrosive oxidation product. In many screening tests for hydraulic fluids and lubricants, oxidation and corrosion are considered concurrently.

5-3.2 MODE OF ACTION OF RUST INHIBITORS

Rust inhibitors are effective through the formation of closely packed hydrophobic monomolecular layers on the surface of the ferrous metal to be protected (Refs. 22-27). Most organic molecules with an adsorbable polar group attached to a hydrophobic chain are effective rust inhibitors. The higher molecular weight polar

compounds are less soluble in oils but have a greater tendency to adsorb on a metal surface and are, therefore, more effective as rust inhibitors. These closely packed films prevent the penetration of water.

Salts or soaps of high molecular weight carboxylic acids—such as naphthenates or sulfonic acids, particularly the petroleum mahogany sulfonic acids—are useful and inexpensive additives for lubricant compositions. These soaps, dispersed in nonpolar solvents, form colloidal systems. The soaps are adsorbed on the metal surfaces and are in equilibrium with low concentrations of soaps in solution, which, in turn are in equilibrium with the soaps in the colloidal micelle. Although the complex equilibria are not fully understood, consideration of the system as one in equilibrium allows the explanation of some of the phenomena associated with the use of these rust inhibitors. These effects include temperature range limitations in the use of the inhibitors, mechanical removal and rehealing of coated surfaces, leaching of the inhibitor from solution with water, and depletion of the adsorbed layers by dilution with hydraulic fluids not containing the inhibitor.

The colloid soap micelle also serves as a “sink” for corrosive acids that are formed as products of oxidation. Sequestration of corrosive acids by the soap micelles offers an explanation why the soaps are better inhibitors than the corresponding acids. The combination of the soap micelle with the corrosive acids may occur through cooperative micelle formation or through hydrogen bonding.

5-3.3 LIMITATIONS IN THE USE OF RUST INHIBITORS

Since the most effective rust inhibitors have low solubilities in the base oils, precipitation during storage may occur when inhibitor concentrations exceed 0.5 to 1.0 percent. Precipitation will be accelerated at low temperatures because inhibitor solubility decreases with decreasing temperature. Compounded lubricants may suffer significant losses in their ability to inhibit rusting after six months' storage because of the precipitation of the inhibitor. Inhibitor insolubility is frequently evident by the development of a haze in the oils.

The varying solubility of an inhibitor in different base fluids results in corresponding differences in inhibitor effectiveness. For example, the minimum concentration of undecyclic acid required for inhibiting a petroleum fluid is 0.20 percent, while 0.75 percent of the same acid is required for di-2-ethylhexyl sebacate, 1.00 percent for a polyalkylene glycol, and 0.20 and

0.50 percent for two silicone fluids (Ref. 22). When large concentrations of an additive are required, less soluble inhibitors should be sought in order to reduce the concentration required for minimum protection.

Because molecular agitation in a liquid increases as temperature increases, the solubility of the additive and, therefore, its tendency for desorption from the metal surface will be increased with temperature. Stated differently, raising the temperature of the oil increases the minimum concentration of the additive necessary to achieve adequate protection. Usually, a temperature is reached above which a rust inhibiting additive is not effective at any concentration. The maximum temperature for the complete inhibition of rusting for several acids in a petroleum oil increases in the following order: linoleic, 115°F; undecylic, 140°F; myristic, 165°F; and stearic, 190°F (Ref. 22). The solubilities of the additives in the oil decrease in the same order.

The adsorbed monolayers can be ruptured by abrasion or wear and leave areas vulnerable to corrosion. If sufficient inhibitor is present in the hydraulic fluid, it will be readsorbed in the scuffed location. The rate of repair will be greater the less viscous the oil.

The presence of water as a contaminant in a hydraulic system may result in the leaching of the monomolecular layer from the surface of the metal or the inhibitor from the hydraulic fluid. The polar nature of most inhibitors allows some solubility in water, which results in the leaching, even though the solubility may be small.

Since the adsorbed monolayer is in equilibrium with the inhibitor in solution, addition of make-up fluid containing no inhibitor to a hydraulic fluid system may ultimately result in the desorption of the monolayer and loss of rust inhibiting properties. Monolayers of compounds, having rust inhibiting properties, on metals can usually be removed by exhaustively washing the surfaces with solvents.

5-3.4 EXAMPLES OF RUST AND CORROSION INHIBITORS

Many classes of compounds are effective as rust inhibitors, namely: sodium and barium mahogany sulfonates; carboxylates, including sorbitan mono-oleate; and a variety of other compounds (Ref. 22). Hydroxyarylstearic acids have been found to function both as oxidation and rust inhibitors (Refs. 28, 29). Nitrogen compounds—such as amines or amides, certain phosphorus compounds (especially esters of phosphorus acids) and dicarboxylic acids made by reacting olefins

with maleic anhydride—are also effective rust preventive additives (Ref. 30).

Impurities present in an additive may have an adverse effect on a hydraulic system. When concentrations of inorganic salts such as calcium chloride or calcium sulfate are present in concentrations as great as 0.12 percent in a mahogany sulfonate, corrosion due to galvanic action may occur (Ref. 31).

When inhibitors are selected to prevent corrosion, the identity of the specific metal-liquid system must be considered since an additive that protects iron may itself corrode copper or silver. An example of the need for a specific inhibitor for a particular system is evident in recent work with fluorocarbon polyether fluids which have proved corrosive to ferrous and titanium alloys in oxidizing atmospheres at 500°F. Perfluoroarylphosphines and phosphine oxides used as additives prevent degradation of the fluorocarbon fluids and the consequent metal corrosion under these conditions up to 650°F (Refs. 20, 21).

Different classes of inhibitors must be used in polar fluids in which water is either a part of the composition or soluble to some extent in the fluid. For example, 0.2 percent of sodium nitrite and 0.8 percent of disodium phosphate dodecahydrate function as corrosion inhibitors in glycerol-water hydraulic fluids containing 40 percent glycerol (Ref. 32).

For inhibiting corrosion of tin, steel, aluminum, cast iron, brass, and copper—in contact with ethylene glycol and 1,2-propylene glycol—the following combinations have proved satisfactory: 0.5 percent borax and 0.5 percent hydroquinone; 0.5 percent triethanolamine and 0.5 percent potassium hydroxide; and 0.5 percent 1,5-dihydroxynaphthalene and 0.5 percent potassium hydroxide. The most satisfactory inhibitors for systems containing *n*-butanol are 0.5 percent hydroquinone with 0.5 percent potassium mercaptobenzothiazole (Ref. 33).

5-3.5 VOLATILE CORROSION INHIBITORS

The polar rust inhibiting compounds described in par. 5-3.4 are effective only on ferrous surfaces contacted by the hydraulic fluid. Corrosion and rust in other parts of the system can be inhibited through the use of volatile corrosion inhibitors which readily sublime at ordinary temperatures and deposit a monolayer on exposed metal surfaces. These inhibitors are often water soluble and can be washed from the surface with water. Although this technique of corrosion inhibition is most frequently used in connection with packaging (Ref. 34), aqueous hydraulic fluids can be inhibited in

both the liquid and vapor phase with diisopropylammonium nitrite (Ref. 35).

5-4 VISCOSITY INDEX IMPROVERS

5-4.1 MODE OF ACTION

The addition of certain polymers to a hydraulic oil will increase the viscosity of the oil throughout its useful temperature range and improve its viscosity-temperature relationship. The contribution of a polymer to the viscosity of a polymer-oil blend is related directly to the effective hydrodynamic volume of the polymer. The hydrodynamic volume of the polymer, in turn, is related to the degree of solvation of the polymer by the base oil (Ref. 36). Higher temperatures favor better solubility of the polymer in the oil hence better solvation and an "expanded" macromolecule. Lower temperatures favor contraction of the macromolecule, or stated differently, the formation of a convoluted species. In this way, the effective contribution of the polymer to the viscosity of the polymer-oil blend is greater at higher temperatures. Not all polymers differ in their contribution to viscosity at different temperatures, but nonetheless they may be referred to as V.I. improvers owing to the inconsistencies of the Dean and Davis viscosity-index system (Ref. 37).

The thickening power of a polymer increases as the molecular weight increases and, consequently, as its effective hydrodynamic volume increases. The thickening power is usually proportional to the molecular weight to the 0.5 to 0.8 power (Ref. 38).

5-4.2 LIMITATIONS

In order to maintain a specified viscosity in a hydraulic fluid at a given temperature, a lower viscosity and therefore more volatile base fluid must be compounded with a polymer thickener because the effect of the additive is to increase the viscosity at all temperatures. In applications where low volatility and low viscosity are required, the use of polymer thickeners will be limited.

A second limitation in the use of V.I. improvers is their susceptibility to shear. In a hydraulic fluid-polymer blend, the extended polymer coil may become oriented under high shear stress with a consequent loss in viscosity. Since the original polymer configuration reforms when the shear force is removed, the term "temporary viscosity loss" has been applied to this phenomenon. An alternate term, "orientation viscosity

loss", has been offered in order to differentiate the effect from the same effect which may result from "thixotropic viscosity loss" of mineral oils below their cloud point (Ref. 37). Also, under high shear stress the polymer chains may be ruptured with a consequent permanent loss in viscosity of polymer-thickened oils. This change, which is not a depolymerization, is more pronounced in blends that contain high molecular weight, or more viscous polymers. Lower molecular weight polymers are less susceptible to "permanent viscosity loss".

The term "shear stability", encompasses both effects, temporary and permanent viscosity loss. Laboratory methods for producing accelerated shearing of polymer-thickened oils have included a mechanical pump loop in which a pump recycles the fluid through an orifice, and a sonic oscillator test method. Since the latter technique offers some advantages over pump loop tests, an ASTM Sonic Shear Method has been proposed (Ref. 39). In studies of the sonic shear test, it has been found that shear breakdown of the polyisobutylenes could be blocked by water contamination, but that the shear stability of polymethacrylates was not significantly affected under similar conditions (Ref. 40). The shear stability of polymethacrylates and polyisobutylenes varies inversely with their ability to improve the viscosity index (Ref. 41). The ability of an additive to improve the viscosity index decreases with applied shear stress (Ref. 42).

Sources of high energy other than shear can also induce degradation of polymer thickeners. These sources include high temperatures, ultrasonic degradation, and gamma irradiation (Ref. 43).

A final limitation in the use of polymeric materials is their solubility in the base fluid and the compatibility of compounded fluids with possible contaminants. Thus, the polymethacrylates have an advantage as V. I. improvers in diester fluids in that the additives are not precipitated when the hydraulic fluid is accidentally contaminated by petroleum oils or the common volatile solvents used to clean hydraulic systems (Ref. 4).

5-4.3 EXAMPLES OF EFFECTIVE POLYMERS

The two classes of polymeric thickeners that have achieved the greatest commercial importance are the polyisobutylenes and the polymethacrylate esters (Ref. 30). The effectiveness of each depends both on the nature of the base fluid, and the particular composition and molecular weight of the polymer. Another class of

useful polymers is that of various paraffinic resins (Ref. 44). Many classes of polymers—including cellulose esters and ethers, polyvinyl alcohols, polyvinyl acetate, polyvinyl acetal, coumarone-indene resins, polystyrenes, polybutenes, and polyacrylic esters—have been examined as potential V.I. improvers and have been found effective.

In synthetic base stocks, a particular thickener must be sought which is effective with the system. The polymethacrylate esters are most effective with diester fluids (Ref. 4); various polydimethylsiloxanes and polymethylphenylsiloxanes have been examined for use with silicate and disiloxane fluids (Refs. 9, 45, 46); and polyaryl ethers have been considered as V.I. improvers for aryl ether fluids, but they increase the already marginally acceptable pour points (Ref. 47).

The amount of a polymer required to blend fluids of a required viscosity, viscosity index, and mechanical stability from a particular base stock is related to the polymer molecular weight (Ref. 48). Blending charts have been developed that allow the prediction of the viscosity of an oil-polymer blend from the polymer molecular weight, polymer concentration, and the viscosity of the base oil (Ref. 49).

5-5 FOAM INHIBITORS, EMULSIFIERS, AND DEMULSIFIERS

Additives useful as foam inhibitors, emulsifiers, and demulsifiers have in common their ability to modify (increase or decrease) the stability of an interface between two phases in a fluid system. Foaming results from the formation of stable gas bubbles in the liquid phase; emulsion occurs with the formation of two stable liquid phases, one dispersed in the other. Foams and emulsions are stabilized by the presence of an adsorbed film at the interface between the two phases.

5-5.1 CHARACTERISTICS OF FOAMS AND THE MODE OF FOAM INHIBITION

The mechanism of foam inhibition is frequently thought to involve changes in the interfacial tension between the liquid and vapor through changing the concentration of polar impurities in the region of the vapor bubble. A number of other theories on the stability of foams and the inhibition of foams have been reviewed by Zuidema (Ref. 50).

Synthetic fluids that are a single chemical compound cannot foam because no impurities are present; however, even highly refined petroleum fluids have the inherent capability of foaming because they are mixtures. Problems with foam are more likely to arise when polar impurities are present. In addition to direct contamination, these polar impurities can come from any of several sources. Accumulated acidic oxidation products or the addition of additives may cause foaming. For example, rust inhibitors frequently contain polar groups and are potential foam stabilizers. A secondary effect is that the possibility of inhibiting foaming may be diminished by the presence of other additives. Thus, an antifoam additive is less effective in a polymer-containing liquid than in one that does not contain a polymeric additive (Ref. 51).

The foaming characteristics of a liquid can depend on a number of operating characteristics, as well as the system design. Temperature, primarily because of its effect on viscosity, is also an important factor in foam stability. Since the collapse of the entrained air can depend in part on the ability of the liquid to flow into the void, a lower viscosity would favor control of foam. Although liquids decrease in viscosity with increases in temperature, foaming at higher temperature can be a serious problem because of the large coefficient of thermal expansion of vapors relative to liquids. Thus, it is reported that, at higher temperatures, foams are more difficult to control in lower-viscosity mineral oils and synthetic hydrocarbons than in high-viscosity materials (Ref. 1).

Several side effects can be observed in connection with foaming. Foaming of an oxidation-susceptible material at a high temperature increases the gas-liquid contact area and time, and consequently the rate at which oxidation occurs. Although foaming is usually associated with air, it may also occur when impurities are present and the gas phase is the vapor of the fluid, and particularly in regions of a system where the local pressure drops to the vapor pressure of the lubricant. Since these are the same conditions that lead to cavitation, the two phenomena are related, and a foam inhibitor may well serve as a cavitation inhibitor.

5-5.2 EXAMPLES OF FOAM INHIBITORS

Methyl silicone oils, for example those with viscosities in the range of 50,000 cSt at 100°F (37°C), are effective foam inhibitors at the remarkably low concentrations of 10 ppm. They are generally considered as "insoluble" inhibitors since they must be present in an

amount that exceeds their solubility to be effective. If the silicones are present in an amount that does not exceed the solubility, or if the insoluble particles are greater in size than 100 microns, they promote foaming (Ref. 52). Other defoamers that have been claimed in the patent literature include the calcium soaps of wool olein, sodium alkyl esters of sulfuric acid, potassium oleate, and esters of sulfonated ricinoleic acid (Ref. 50). Other reportedly useful additives are halogenated compounds, organic sulfates, polyesters, polyhydroxy esters, polyhydroxy alcohols, and hydroxyamines (Ref. 51).

5-5.3 EMULSIFIERS AND DEMULSIFIERS

Emulsions consist of two immiscible or partly miscible liquid phases, a dispersed phase of small particles in a continuous phase. Since the lubricating properties of an emulsion will approximate the lubricating properties of the continuous phase, certain water-in-oil emulsions have received attention as fire-resistant hydraulic fluids (Ref. 53). These emulsions, which usually contain about 40 percent water, are stabilized by emulsifying agents that are characterized as molecules having one group of atoms that is hydrophilic and a second group of atoms that is oleophilic. A molecule so constructed is capable of orienting itself at an oil-water interface, decreasing the interfacial tension, and stabilizing the emulsion. These additives, which may frequently be organic acids or soaps, can be selected from known classes of nonionic, anionic, or cationic surface active agents.

More often in hydraulic systems, additives that induce demulsification are required. Impurities that cause foaming can also cause emulsions if water happens to be present in the system. If the water is emulsified and cannot be readily removed through drainage, lubricated parts can be damaged. Polar impurities can influence the development of either water-in-oil or oil-in-water emulsions.

The selection of a suitable demulsifying agent will depend in part on whether an oil-in-water or a water-in-oil emulsion must be counteracted. An additive that stabilizes an oil-in-water emulsion will generally destroy a water-in-oil emulsion, and vice versa. Thus, most demulsifiers are also surface active agents. Some examples of specific additives are petroleum sulfonic acids, or salts; dimerized, unsaturated, aliphatic monocarboxylic acids; and sulfonated castor oil (Ref. 8).

5-6 LUBRICITY

5-6.1 HYDRODYNAMIC VS BOUNDARY LUBRICATION

Lubricity is a measure of the ability of a lubricant to reduce the friction or wear between two solid surfaces in contact with each other. The lubricant may be called upon to reduce friction in one of several ways, depending on the film thickness and the particular conditions under which the system is operating. Two important variables are temperature and pressure, which in turn will influence the film thickness of the lubricant between the two surfaces being lubricated.

When the film thickness is greater than about 25 millionths of an inch, the mode of lubrication is hydrodynamic. Under these conditions, the moving surfaces never come in contact with each other and the friction is largely determined by the viscosity of the lubricating fluid. The only additives of importance in hydrodynamic lubrication are polymer additives because they increase the viscosity of the fluid.

As the pressure or temperature between the lubricated surfaces is increased, the lubricating film can become sufficiently thin that metal-to-metal contact occurs and boundary lubrication develops. Under these conditions the fluid serves as a carrier for boundary or extreme pressure additives and as a coolant.

5-6.2 OILINESS, ANTIWEAR, AND EXTREME-PRESSURE ADDITIVES

Additives for boundary lubrication are divided into three somewhat indefinite classes—oiliness agents, antiwear additives, and extreme pressure additives—the classification being made on the basis of the stringency of the temperature and pressure requirements—temperature being the more important of the contributing factors. Each of the three classes of additives is effective insofar as it modifies a lubricated surface, reduces the friction, or protects the surface from damage.

5-6.2.1 Oiliness Additives

Oiliness additives, which are usually effective at low temperatures and pressures, are polar molecules that can form monomolecular films on a lubricated surface. The most frequently cited example is oleic acid. Oleic acid forms an oriented film that has a relatively high energy of displacement at the interface of the lubricant

and the metal by adsorption of the acid portion of the molecule on the metal surface.

5-6.2.2 Antiwear Additives

Phosphorus-containing additives are usually classed as antiwear additives. Under higher pressures and temperatures, these additives are thought to be effective in reducing wear through their ability to form iron (II) phosphate and its hydrate on the metal surface (Ref. 54). The formation of the iron (II) phosphates has been attributed to the presence of polar impurities, perhaps acidic hydrolysis products, of the phosphate (Refs. 55-57). The most common example of this type of additive is tricresyl phosphate which is frequently used in conjunction with an oiliness agent.

5-6.2.3 Extreme-pressure Additives

Extreme-pressure additives are used under the most severe conditions and are usually sulfurized or chlorinated organic materials. Compounds containing benzylic sulfur are particularly effective. Under conditions of extreme pressure or temperature, welding of the two mating surfaces can occur with consequent seizure, galling, or scuffing. In a lubricant containing an extreme pressure additive, when high temperatures that can produce welding are approached, the additive presumably undergoes a chemical reaction with the metal surface to form a metal chloride or sulfide film that protects the surface. The sulfur-containing additives may be used with lead naphthenate to obtain a protective lead-sulfide coating.

5-6.3 CLASSES OF LUBRICITY ADDITIVES

Lubricity additives function through their action at the surface of the metal to be lubricated; therefore, lubrication of different metal combinations may require the use of different additives. All base stocks are not equally susceptible to additive modification, and the effectiveness of antiwear additives can be modified by the presence of other additives. For these reasons, a very large number of compounds and materials have been investigated as potential boundary lubricants in hydraulic fluids.

5-6.3.1 Additives for Mineral Oils and Esters

Ester-based fluids and mineral oils are readily susceptible to additive modification with a variety of

materials. Phosphates and phosphites, particularly tricresyl phosphate, have received considerable attention as additives (Ref. 1). Acid phosphates and even phosphoric acid show antiwear properties in the proper concentration, but too large a concentration of phosphoric acid can lead to chemical erosion (Ref. 1). Phosphates and phosphonates containing long alkyl chains provide good lubricity and, in addition, function as antioxidants (Ref. 58). The effectiveness of tricresyl phosphate is reduced in the presence of polar compounds such as petroleum sulfonates, which have a greater affinity for metal surfaces than does tricresyl phosphate (Ref. 1). Metal dithiocarbamates function as antiwear additives in ester fluids, but not in mineral oils. Fluorinated esters have been found to be as susceptible to antiwear additives as nonfluorinated esters (Ref. 59), but many additives are not sufficiently soluble to be used in the fluorinated esters.

5-6.3.2 Additives for Silicon-containing Fluids

A great many additives that are effective in mineral oil and ester fluids are ineffective in silicones, silicates, and siloxanes. Silicones show especially poor additive susceptibility for lubricating steel-on-steel. The wear properties can be improved in ester-silicone blends, but such a high proportion of ester is required that the good high-temperature properties of the silicones are lost (Ref. 1).

Silicon-containing liquids are usually not susceptible to modification by antiwear additives. There is evidence that the silicon reacts preferentially with the metal to be lubricated, forming a coating on the metal that is no longer reactive with the antiwear additive. Silicones and silicates themselves can be used as additives in esters and mineral oils to obtain antiwear properties, a fact which suggests that a soft, inert silicon-iron alloy is formed (Ref. 1). Some attempts have been made to modify the chemical structures of silicones to improve their wear properties. Friction and wear studies of chlorinated methylphenyl silicones show an improvement over nonhalogenated methylphenylsilicones, but high friction and wear are still observed with hard steel on soft steel and soft steel on soft steel (Ref. 60). In addition, the chlorine-modified silicones suffer a second limitation in being poorer lubricants for steel on copper above 400°F than are unmodified silicones (Ref. 60). A great improvement in the lubricity of chlorinated phenylmethylsilicone was found when the liquid was cooked with tin tetrachloride (Ref. 10). Fluorosilicone fluids are reported to have at least

equivalent wear performance on the Shell 4-Ball Extreme Pressure Tester to di-2-ethylhexyl sebacate (Ref. 61).

A final class of silicon-containing fluids, the tetraalkylsilanes, have better additive susceptibility than the silicones, silicates, or siloxanes. Although tetraalkylsilane base fluids exceed target wear limits, their wear properties can be improved with phosphates, phosphites, phosphonates, phosphorothioates, and sulfonated petroleum derivatives (Ref. 62).

5-6.3.3 Additives for Aryl Ether Fluids

A variety of additives have proved effective in imparting improved wear properties to poly(phenyl ethers) (Ref. 16). These additives include bis(cyclopentadienyl)titanium bis(trichloroacetate) and its polysulfide derivative, diphenyltin bis(trichloroacetate), bis(triphenylphosphine)nickel dichloride, and particularly, trichloroacetic acid. Tricresyl phosphate at the 5 percent level is also effective in aryl ethers (Ref. 63).

5-7 POUR POINT DEPRESSANTS

An oil that does not readily crystallize may be cooled to a temperature at which the viscosity becomes so great that it will not flow under the conditions of the pour point test. This viscosity or glassy pour point is inherent in the chemical nature of the oil and can be modified only through the blending of oils or mixing the oils with light diluents.

Petroleum oils that contain a small percentage of wax may cease to flow at a much higher temperature owing to the formation of a network of wax crystals. Such a "waxy" pour point may be lowered through the use of additives. A number of explanations have been offered for the mode of action of these additives, but their effect is thought to depend on the additive's ability to modify the crystallization process so that more and smaller crystals with a higher volume-to-surface area ratio are obtained. The modified crystals do not form networks so easily (Refs. 64-65).

Materials that are used as commercial additives include the polyalkylnaphthalenes, polymethacrylates, and alkylated polystyrenes. Other polymeric additives are also effective (Ref. 66).

5-8 SEAL DEGRADATION RETARDANTS

It is desirable that elastomeric seals swell to some extent (about 5 percent) when they are in contact with

a hydraulic fluid in order to more effectively seal the system. Certain fluids, however, notably the silicates and siloxanes, are poor rubber solvents but good solvents for rubber plasticizer. The result is that the plasticizer can be extracted from the rubber with consequent shrinking and hardening.

The approach to solving this problem is the addition of 5 to 15 percent of compounds to the fluids that can act as rubber plasticizers (Refs. 9, 46, 67). Esters such as butyl oleate, di-2-ethylhexyl sebacate, and dibutyl phthalate, and certain aromatic compounds have been most commonly used in this application. With such large quantities, the function of the added material is not so much an additive as a modification of the base liquid through blending. In so modifying a liquid, special attention must be given to changes in the physical properties.

5-9 HYDROLYTIC INHIBITORS

Silicate esters undergo hydrolytic degradation to produce products that are both corrosive and insoluble; carbocylate and phosphate esters seldom yield insoluble products on hydrolysis. Chief interest in finding additives that will correct these undesirable properties has been in connection with silicate and disiloxane based fluids, although phosphates, phosphonates, and carbocylates have received some attention. Properly inhibited, silicate fluids have been shown to have acceptable hydrolytic stabilities (Ref. 67). In designing a hydraulic fluid, it is often preferable to modify the chemical structure to obtain hydrolytic stability rather than to use inhibitors.

Without inhibitors, many silicates tarnish copper and deposit some silica under conditions of hydrolysis at 200°F, but additives such as metal phenates, phenyl - α - naphthylamine (Refs. 45, 68), N, N'-dibutyl - *p*-phenylenediamine (Ref. 9), and *p,p'*-dioctyldiphenylamine (Ref. 46) are effective at a concentration of 0.1 percent in stabilizing the fluid. Since the aromatic amines are effective inhibitors in concentrations less than those required for their use as antioxidants, the additive can serve a dual purpose. Diphenylamine and phenothiazine are less effective, and phenolic inhibitors are ineffective (Ref. 68).

The inhibitors lose their effectiveness after a compounded hydraulic fluid is exposed to the rubber swell test, presumably as a result of the leaching of the plasticizer from the rubber (Ref. 9). The additives are not effective in 400°F hydrolytic stability tests (Ref. 46).

5-10 CAVITATION INHIBITORS

Cavitation is a poorly understood phenomenon. There are few data available in the literature on the use of additives to change the cavitation resistance of hydraulic fluids. The usual procedure to avoid damage to structural parts of the hydraulic system from cavitation in the hydraulic fluid is to use materials that are resistant. Softer metals are plastically deformed; hard brittle metals are pitted. Hard, tough metals, such as cobalt chromium alloys, are very resistant to damage (Ref. 69).

There has been some development work, however, on cavitation inhibiting additives. Studies in the literature suggest that if the cavities consist of a vacuum or the vapor of the liquid, they will collapse with more energy release than if they contain some foreign gas, such as air (Ref. 69). The work that has been done on cavitation inhibitors has been directed toward "filling" the cavities with a "foreign gas".

One of the most successful cavitation inhibitors is water. Although reports are contradictory as to the performance of water, it was used in one study at a ratio of 1:200 in a hydraulic fluid to reduce cavitation erosion in control valves (Ref. 70). The hydraulic fluid was a commercial phosphate ester liquid. Results indicated almost complete elimination of the cavitation damage that had been occurring with the "unwatered" hydraulic fluid. Theoretical work on the use of water in a phosphate ester indicated that 0.5 percent water would increase the vapor pressure and reduce the cavity collapse pressure (Ref. 69).

Several reports summarized in Ref. 69 have shown that some additives, as well as some contaminants, increase the actual damage from cavitation. The consensus expressed in the literature is that every property of a liquid has a two-fold and opposing effect on cavitation and the resultant damage. The various effects are often interacting and complex. The limited data available suggest that many of the candidate additives for cavitation inhibition may reduce the total amount of cavitation present but increase the resulting cavitation damage.

5-11 BIOCIDES

Biocides are additives designed to inhibit the growth of micro-organisms in liquids. The Air Force, Army, and many petroleum companies have sponsored research concerning microbial attack and growth in petroleum products used as fuels (Refs. 71, 72). However, there has been almost no work on micro-organisms in

hydraulic fluids. In general, hydraulic fluid specifications contain no requirements on inhibiting microbial growth. But microbial deterioration of hydraulic fluids can be a real problem and should be considered in the selection of a suitable liquid. In some instances, it will be necessary to add an inhibitor or a biocide to prevent growth.

For a biocide to be successful and desirable, it must: (a) have low toxicity to the skin or upon inhalation, (b) be soluble in hydraulic fluids and their additives, (c) be noncorrosive to metals, (d) be economically suitable (inexpensive or effective in very low concentration), and (e) have no degrading effect on other properties of the liquid such as viscosity, stability, fire resistance, etc. Although there are numerous effective inhibitors available, none satisfy all of the above requirements. Many potential inhibitors are toxic to humans and many that are effective are too expensive or require such large concentrations that they change the properties of the liquid.

Because many liquids used as hydraulic fluids and all jet fuels are hydrocarbons, the biocide research results for jet fuels are, in general, applicable to hydrocarbon hydraulic fluids. Ethylene glycol monomethyl ether (EGME) and glycerol is a water soluble additive that is effective as a biocide in jet fuel. It has been reported that as little as 0.05 percent by volume keeps micro-organism growth to a minimum (Ref. 73). Quaternary ammonium acetate, ethylidene diacetate, and tri-*n*-butyl borate are other inhibitors recommended for use in jet fuel in bulk storage tanks (Ref. 74). In some instances, other additives such as antioxidants or anti-icing compounds have been found to have a secondary effect as biocides (Ref. 75).

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CHAPTER 6

STORAGE AND HANDLING

6-1 CONTAINERS

6-1.1 GENERAL

The function of hydraulic fluid containers is simply to contain the fluid during transport and storage. The container must be strong and tight enough to assure protection of its contents, and it must preserve the original cleanliness of the fluid. Characteristics important to the design and selection of containers for a specific hydraulic fluid include the container materials, dimensions, and storage conditions to which the container will be subjected. Also of importance are standards for proper labeling, and guidelines for the purchasing and ordering of containers.

6-1.2 CONTAINER MATERIALS

Industrial and military requirements for materials for hydraulic fluids containers vary, but the usual materials are steel or aluminum. In general, military hydraulic fluid specifications for containers for one gallon or less require that they be packaged in metal cans, 28 gage or lighter, conforming to Federal Specification PPP-C-96A (Ref. 1). Heavier gage steel is used for containers of 5- and 55-gal capacities. For instance, 55-gal drums must comply with Federal Specification PPP-D-729B (Ref. 2) and range from 12 to 18 gage; 5-gal containers must comply with Federal Specification PPP-P-704B (Ref. 3) and range from 24 to 26 gage.

Exterior coatings for military purposes usually conform to Federal Specification TT-E-515 (Ref. 4) for quick-drying enamel. Containers of one gallon or less are generally painted red, while larger containers are painted olive drab. Exterior coatings for commercial use depend on the manufacturer's preference and frequently incorporate a color code to distinguish the contents.

Interior coatings or liners are common for hydraulic fluid containers made for commercial use, especially the 55-gal drums. For Military Specification fluids, however, interior coatings or liners generally are not required. When interior coatings or liners are used, they must be of a material that will not react with the hydraulic fluid.

6-1.3 CONTAINER SIZES, STORAGE, AND MARKING

MIL-STD-290C (Ref. 5) includes detailed information regarding required methods of packaging, packing, and marking of hydraulic fluid containers. Table 6-1 and Figs. 6-1, 6-2, and 6-3 list and illustrate applicable data regarding size.

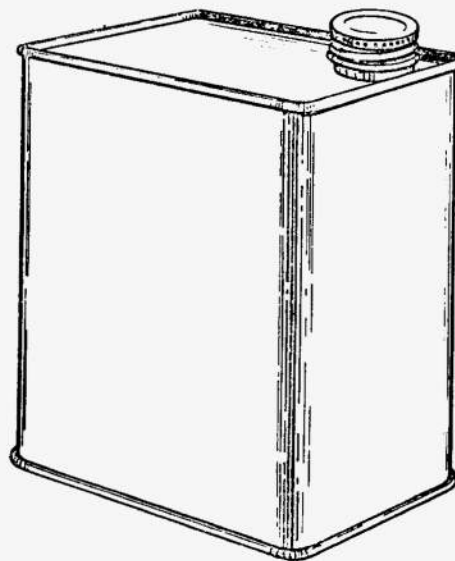


Fig. 6-1. One-gal Screw Cap Can, Type V, Class 4

TABLE 6-1.
HYDRAULIC FLUID CONTAINER SIZES⁵

Container	Container Capacity	Type	Class	Cap Design	Shape
Can	1-pint	V	4,8	Screw cap, spout, or special closure	Oblong
Can	1-quart	V	4,8	Screw cap, spout, or special closure	Oblong
Can	1-quart	I	—	Hermetically sealed	Cylindrical
Can	1-gallon	V	4,8	Screw cap, spout, or special closure	Oblong
Can	1-gallon	I	—	Hermetically sealed	Cylindrical
Pail	5-gallon	—	—	Screw cap, spout, or special closure	Cylindrical
Drum	55-gallon	—	—	Bung	Cylindrical

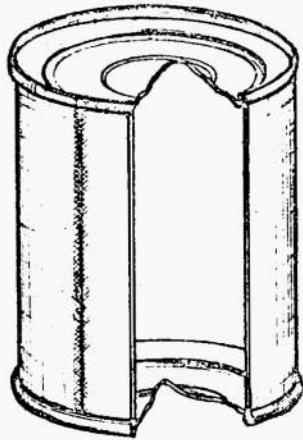


Fig. 6-2. One-qt Hermetically Sealed Can, Type I

Storage requirements are frequently included in hydraulic fluid specifications. For example, MIL-H-5606B hydraulic fluid specification states that "prior to use in the intended equipment, the product may be stored under conditions of sheltered or unsheltered storage in geographic areas ranging in temperature from -57° to $+49^{\circ}\text{C}$ (-70° to $+120^{\circ}\text{F}$)" (Ref. 6). Hydraulic fluid specifications often include storage stability requirements which a liquid must pass to become qualified under the specification. For example, in MIL-H-8448B (Ref. 7), a candidate liquid must pass the following storage test: "Three 4-oz samples of the test fluid shall be placed in separate airtight glass containers and stored in the dark at temperatures between 65°F (18°C) and 90°F (32°C) for a period of 12 months. No

agitation of the samples shall be permitted during storage of the samples. The samples shall then be examined visually to assure that they exhibit no formation of resinous gums, sludges, or insoluble materials or separation."

Marking instructions required on hydraulic fluid containers for military use are given in MIL-STD-290C (Ref. 5). References given in MIL-STD-290C (Ref. 5) specify the colors and types of inks (Ref. 8), lacquers (Ref. 9), and enamels (Ref. 10) to be used for marking containers. The information normally required on large containers, and its proper location, is illustrated in

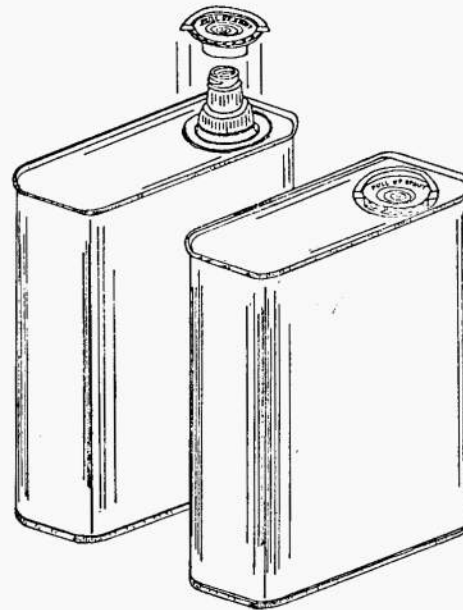


Fig. 6-3. One-pt Spout Top Can, Type V, Class 8

Figs. 6-4 and 6-5. The numbers in parentheses on Fig. 6-5 refer to the letter size to be used. The abbreviations listed in Table 6-2 are frequently used for hydraulic fluid container marking.

TABLE 6-2.
RECOMMENDED ABBREVIATIONS⁵

a. Quantitative Units	
Dozen	DZ
Each	EA
Gross	GR
Hundred	HD
Thousand	MX
Weight	WT
Cube (cubic foot)	CU
Gallon	GA
Quart	QT
Pint	PT
Ounce	OZ
Cubic Centimeter	CC
b. Procurement Marking Abbreviations	
Aircraft	ACFT
Automotive	AUTO
Engine	ENG
Lubricating	LUBE
Petroleum	PETRO
Preservative	PRESERV
Temperature	TEMP
Turbine	TURB
Reciprocating	RECIP
Gyroscope	GYRO

Caution, warning, and instruction markings are sometimes required on containers. For example, MIL-H-27601A containers must include the following markings (Ref. 11): "*INSTRUCTIONS: Destroy all markings on this container when empty. Do not mix with any fluid except those of MIL-H-27601 and revisions.*"

6-2 CONTAMINANTS

Fluids used in hydraulic systems must meet high standards of purity. Malfunctions in hydraulic systems frequently can be traced directly to contaminated hydraulic fluids. Although contamination can often be attributed to sources not related to the handling and storage of the hydraulic fluid (such as contamination particles due to system wear), many problems can be eliminated by proper handling and storing of hydraulic fluids.

6-2.1 SOURCES OF CONTAMINATION

There are many sources of hydraulic fluid contamination. Some of the more common are: (1) lint and dust, (2) moisture, and (3) additive problems.

6-2.1.1 Contamination from Lint and Dust

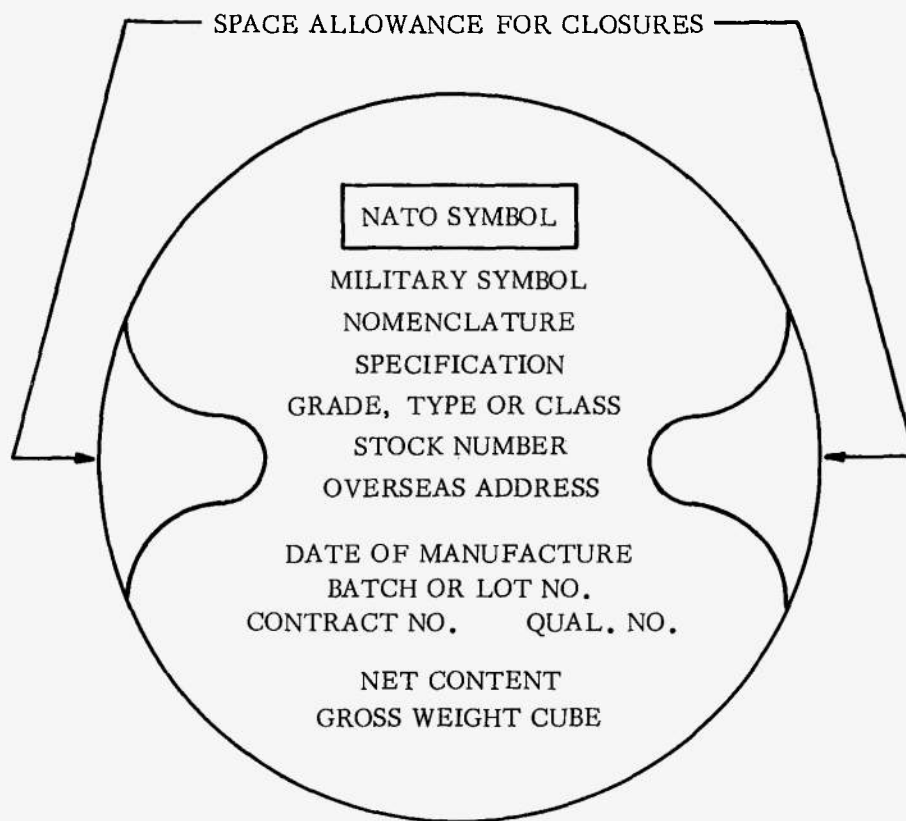
Lint, dust, and other foreign matter should be the least common type of fluid contaminant. Their source can usually be traced to carelessness on the part of personnel who handle the fluid. Airborne dust can enter the container when it is left uncapped or improperly sealed. Lint and other foreign matter can be traced to careless procedures in wiping lids, funnels, and other items which come into contact with the fluid.

6-2.1.2 Moisture Contamination During Storage

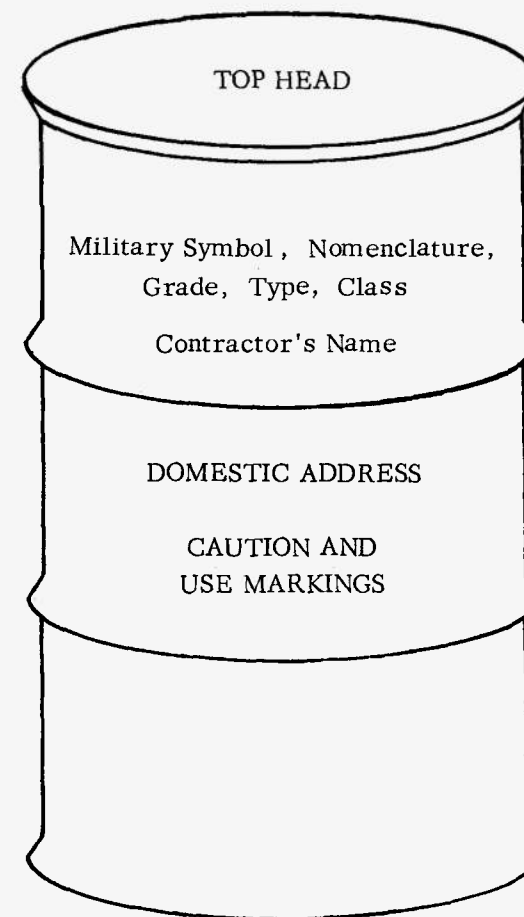
Moisture is one of the greatest enemies of hydraulic fluids and systems, except for aqueous type hydraulic fluids and the systems designed to use them. In general, special care should be taken to make containers waterproof—especially when they are stored without protection from the weather. Introduction of moisture into waterproof containers by "breathing" and condensation is a problem whenever containers are exposed to frequently and widely varying temperatures. For this reason, storage conditions where such problems can occur should be avoided. Containers stored out-of-doors should be stored on their sides to prevent water from standing on container tops. Container lids and bungs should be periodically checked for tightness.

6-2.1.3 Contamination Accompanying Additives

Impurities accompanying additives are, in the strictest sense, a manufacturing problem but one which may ultimately become the headache of the hydraulic fluid handler. For example, it has been reported that an additive in some MIL-H-5606B fluids has, on occasion, been found to contain a contaminant soluble in the additive itself but insoluble in the finished hydraulic fluid (Ref. 12). Some additives for hydraulic fluids can cause considerable contamination problems when moisture accumulates in the hydraulic fluid. Hydraulic fluids with corrosion inhibitors are prone to form a slime with moisture contamination (Ref. 12).



(A) Top Markings



(B) Side Markings

Fig. 6-4. Markings on Top and Side of 55-gal Drum

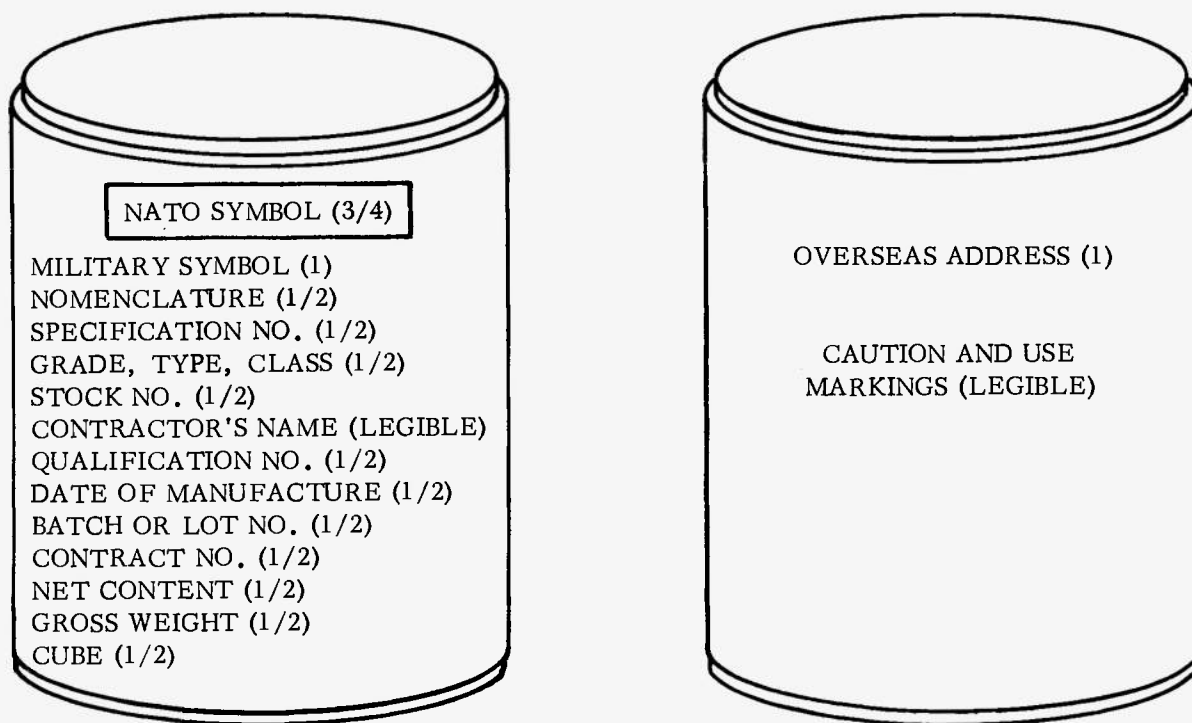


Fig. 6-5. Markings on Sides of 5-gal Tight-head Pail

Mahogany sulfonate rust inhibitors widely used in finished hydraulic fluids can also be a source of contamination, i.e., rusting and staining of steel in a hydraulic system. It has been found that some mahogany sulfonates contain inorganic water soluble salts (such as calcium chloride and calcium sulfate) ranging from 0.02 to 0.19 percent. Data show that the concentration of inorganic salts do not appear to affect the rust prevention properties of the mahogany sulfonates, but their presence does produce corrosion due to galvanic action. It was found that use of petroleum hydraulic fluids containing sulfonates with a relatively high chloride content of 0.12 percent produced system malfunctions while use of petroleum hydraulic fluids containing sulfonates with less than 0.03 percent of the salt permitted satisfactory operation (Ref. 13).

6-2.2 TYPES OF CONTAMINANTS

The many impurities that can affect hydraulic fluids adversely can be classified as either solid particle or liquid contaminants. The most common and most troublesome liquid contaminant is water, but liquid contaminants include all foreign liquids, both miscible and

immiscible. Solid particle contaminants are self-defined. They are impurities which may either be chemically reactive with hydraulic fluids or which may foul hydraulic systems.

6-2.2.1 Water As a Contaminant

Although water was the first liquid to be used in a hydraulic system, it is generally a harmful contaminant (Ref. 14) in current sophisticated hydraulic systems. Depending on the properties of the liquid under consideration, water will either form an emulsion in the hydraulic fluid (up to a certain percentage) or be partially immiscible with the hydraulic fluid with some water floating on the surface of the hydraulic fluid or settling to the bottom of the container. Immiscible or free quantities of water in a hydraulic fluid are usually the result of careless handling and cause damage to both the hydraulic fluid and the system. Unwanted water in a hydraulic fluid leads to a multitude of problems in terms of hydraulic system damage and failure. The worst threats of water contamination are the corrosive effects of water and the subsequent fluid and/or system contamination with corrosion particles.

One clarification concerning water and hydraulic fluids must be made, however. In certain fire-resistant hydraulic fluids, water is a welcome ingredient, making up from 20-70 percent of the liquid. Such fire-resistant hydraulic fluids are formed by an emulsion of water dispersed in a second liquid, such as oil or a glycol. In these liquids the distinction between water as a needed ingredient and water as a contaminant is clear.

A distinction must be made between oil-in-water emulsions and water-in-oil emulsions. Although a stable solution can be made by dispersing oil in water, problems with corrosion and wear are more apt to occur with this type of emulsion. "Inverse" or water-in-oil emulsions, on the other hand, offer the fire-resistant quality of water while retaining the lubricating and anticorrosion qualities of the oil. In "inverse" emulsions, water is the dispersed phase while oil is the continuous phase. In oil-in-water emulsions, the situation is reversed—the oil is the dispersed phase and the water is the continuous phase.

6-2.2.2 Solid Contaminant Particles

Of all contaminants, solid particles are of most frequent concern. Their measurement is usually determined according to size and number. The cleanliness of a hydraulic fluid is normally reported as the relative "solid particle cleanliness".

Solid particle contaminants are either of the fibrous or nonfibrous variety. Fibrous particles have a large length-to-diameter ratio. A fibrous particle has been defined by Aircraft Industries Association as one having a length-to-diameter ratio greater than 10 to 1. Nonfibrous solid particle contaminants include all particles not in the fibrous class. Their irregular shapes make it necessary to define their size by their largest dimension.

The unit of measurement for solid particle contamination is the micron (about 39 millionths of an inch). The normal human eye can detect particles as small as 40 microns. However, contaminant particles as small as 1/2 micron may be of concern.

Because of the wide variety of hydraulic fluids and their equally wide variety of applications, there are many standards of fluid cleanliness. MIL-H-5606B requires that (1) there be no particles over 100 microns in size, and (2) the total contamination in a 100-ml sample retained on a 0.45-micron cellulose filter be no more than 0.3 mg.

Table 6-3 presents data on generalized contamination limits for hydraulic fluids as proposed by the Aircraft Industries Association (Ref. 15). It is not to be

considered as a standard for all hydraulic fluids. Indeed, if contamination levels are to be established for a hydraulic fluid, it is best to refer to the manufacturer's data for the most reliable indication of the contamination limits and to take into account the design of the system(s) in which the liquid will be used.

Table 6-4 is an example of contamination limits for hydraulic fluids established by one aircraft company (Ref. 15). Not only is the maximum number of particles specified, but the maximum weight of the contaminant per 100 ml of liquid is also specified. The differences in contamination limits between Tables 6-3 and 6-4 serve to illustrate the relative nature of fluid "cleanliness". What may be a "clean" fluid in one application may not be "clean" enough for another. The specific application of the fluid is always the ultimate factor in determining contamination limits.

6-2.2.3 Liquid Contaminants Other Than Water

In addition to solid particle and water contamination, contamination from other liquids, both miscible and immiscible, can occur.

Liquid contaminants in hydraulic fluids often enter a system as a result of mixing (accidental or intentional) two or more hydraulic fluids. Accidental mixing often occurs when replacing the hydraulic fluid in a system with another hydraulic fluid without a thorough cleaning of the system. Liquid contamination of a hydraulic fluid can also occur when transferring the liquid into unclean containers. In general, such transfers should be avoided. In some cases, however, Military Specifications indicate that two different liquids are compatible and may be mixed. Such a mixture may be considered usable in that it does not form resinous gums, sludges, or insoluble solid materials; however, the liquids in the mixture are contaminated in the sense that the liquids may no longer retain their original characteristics. Such characteristics may be critical in certain applications that require a "clean" fluid.

Contamination of a hydraulic fluid by oils or solvents used in or on the hydraulic system is a frequent form of contamination. This type of contamination reduces the effectiveness of the hydraulic fluid by changing characteristics such as viscosity, density, and lubricating ability or by attacking system components such as seals. However, the oil or solvent may have no chemical effect on the hydraulic fluid itself, particularly in the case of petroleum base hydraulic fluids and petroleum fraction oils or solvents (Ref. 12).

TABLE 6-3.
AIA PARTICLE CONTAMINATION LIMITS FOR HYDRAULIC FLUIDS¹⁵

Class	Number of Particles					
	Particle Size, μ				Particle Size > 100 μ^d	
	5-10 ^a	11-25	26-50	51-100	Fibers ^b	Particles ^b
1	—	220	20	5	2	0
2	—	530	60	10	3	1
3	—	1,530	150	15	4	1
4	—	5,530	420	40	7	3
5	—	1,650	320	25	1	0 ^c

Notes:

- Value to be controlled for each application.
- Particles with length-to-width ratio greater than 10 are termed "fibers;" with length-to-width ratio less than 10, they are termed "particles."
- Zero particles are defined as none if one sample is taken; if an average of several samples is taken, total particles in all samples must be less than number of samples to meet "zero" requirement.
- μ = 1 micron = 10^{-4} cm

TABLE 6-4.
PARTICLE CONTAMINATION LIMITS FOR
HYDRAULIC SYSTEMS AT MARTIN AIRCRAFT COMPANY¹⁵

Type System	Maximum Filterable Solids, mg/100 ml	Maximum Particles and Fibers	
		Size, μ^*	Number/100 ml
Airborne	2.0	0-25	Unlimited
		25-100	250
		Over 100	10
Ground	3.0	0-25	Unlimited
		25-100	750
		Over 100	80

* μ = 1 micron = 10^{-4} cm

Chemical contamination of a hydraulic fluid is generally a rare occurrence and difficult to trace. Some instances of chemical contamination have been explained by deposits of cleaning compounds left on surfaces, or by reaction of an additive with seals or filters, and other such unusual instances. However, one recurring source of chemical contamination is a contaminant that is soluble in an additive but is insoluble in the finished fluid (Ref. 12).

6-2.2.4 Microbiological Contaminants

Micro-organisms can grow in hydraulic fluids to some extent. However, most of the problems associated with this type of contamination occur in the handling and use of aviation fuels, and most of the research work pertains to the effect of microbiological contamination of fuels. The problem deserves a discussion in relation to hydraulic fluids, however, because microbiological

contamination can occur in hydraulic fluids. If sufficient quantities of the organisms are allowed to grow unchecked, they can clog filters, restrict small orifices, and cause poor operation of close tolerance parts.

The growth of micro-organisms can be increased by the presence of other contaminants in the hydraulic fluid. Water contamination, for example, provides an environment, and is necessary, for the growth of living organisms. In most cases, elimination of microbial contaminants with biocides does not solve the underlying contaminant problems that originally contributed to growth of the micro-organisms (Ref. 16).

6-2.3 EFFECTS OF CONTAMINATION

Contamination in a hydraulic system is damaging to the hydraulic fluid and to the system in which it is used. The degree of contamination usually begins at a low level and increases because of the formation of contaminants in the system itself (especially solid particle contaminants caused by system wear, oxidation, and corrosion).

6-2.3.1 Effects of Contamination on the Hydraulic Fluid

Once a hydraulic fluid becomes contaminated, it is usually no longer suitable for use. The destructive effects of contamination are often of a "chain-reaction" nature and produce further damage to the liquid. While this is not always the case, it is easier to prevent damage by avoiding contamination through proper handling and storage techniques than it is to make repairs that may be required as a result of using contaminated liquid.

There are a number of situations where contamination can grow even within a closed and sealed system. One example of the "chain reaction" that can occur is the effect of moisture in hydraulic fluids without anticorrosion additives. Corrosion particles resulting from moisture, in effect, act as wear particles which expose clean metal surfaces that subsequently succumb to corrosion (Ref. 12).

It has been observed that the presence of solid particle contaminants can affect the oxidation resistance of hydraulic fluids. Although most hydraulic fluids contain oxidation inhibitors, their intended effect can be seriously depleted when solid particles accelerate oxidation of the fluid and "use up" the inhibitor (Ref. 12). When excessive contamination thus "wears out" the oxidation inhibitor, the hydraulic fluid can easily succumb to the effects of oxidation and, consequently, the formation of corrosion products.

Solid particles on the order of 100 microns can be formed from smaller ones. This effect has been especially noted in noncorrosion-preventing petroleum base hydraulic fluids (Ref. 12). These fluids are highly dielectric and contaminant particles retain a static charge. The result is that when the fluid is exposed to long periods of agitation, such as in shipping, the probability of particles colliding with one another increases and particle agglomerations form. Fluids with submicronic particles have been known to form 25- to 200-micron particles under these conditions (Ref. 12).

Moisture is a contaminant which causes a slime in some hydraulic fluids. The necessary ingredients for the formation of this slime that can clog filters are tricresyl phosphate (an antiwear additive used in several hydraulic fluids), an alkali, and moisture (Ref. 12).

In a hydraulic fluid of the corrosion-preventive type, moisture can also cause the formation of a slime resembling egg white. When sufficient moisture is present, the corrosion-preventing additives can exhaust themselves by "wrapping up" the moisture in additive and water dispersions (Ref. 12).

6-2.3.2 Effects of Contamination on the Hydraulic System

System damage or failure may be caused in a number of ways. Solid particle contaminants may result in friction and wear, jamming, or seizing. In hydraulic mechanisms where close-fitting parts move at relatively high speeds, solid particle contaminants shear the faces of system components. The buildup of more and more wear particles can, therefore, result from an initially small amount of solid particle contamination. Since moisture may also produce solid particle contaminants due to corrosion, its ultimate effect can be the same—more and more contaminant buildup. Plugging of small openings and filters may result from solid particle contamination or from the formation of slimes.

Hydraulic system fouling can also be caused by the chemical interaction of hydraulic fluids with seals. It is a design error to use seals or other system components that would be reactive with the fluid. The result is formation of gels, sludge, and abrasive particles that can further damage a hydraulic system.

A convincing illustration of the ill effects of hydraulic fluid contamination is to compare system life under controlled contamination levels with system life under the best contamination free conditions allowed by present technology. One report examines the effect of various controlled solid particle contamination levels on servo-valve internal leakage. One conclusion reached,

which is indicative of the effects of at least solid particle contaminants, is that normal contamination can be controlled to the point where the life of a servo-valve assembly can be increased by as much as 277 percent (Ref. 17). Table 6-5 presents data on some of the many types of contaminants and their general effects on the most common components in a hydraulic system. (Ref. 18).

6-2.4 METHODS OF DETERMINING CONTAMINATION

The required cleanliness of a hydraulic system is relative and is dependent on the design of a particular system. Although the criteria for cleanliness may vary for different systems, the methods of contaminant measurement are basically alike. Methods of solid particle contaminant measurement involve counting, sizing, and/or weighing of the particles in a given volume of fluid. Methods of determining the amount of liquid contaminants present in hydraulic fluids usually involve chemical or physical procedures—distillation, separation with a solvent, or isolation of the contaminant by chemical reaction.

6-2.4.1 Solid Particle Contamination Measurement by Counting

(1) Microscope Methods:

Three test procedures for determining the solid particle contamination in hydraulic fluids by counting are

in general use. They are: Federal Test Method 3009 (Ref. 19), ASTM D-2390 -65T (Ref. 20), and Aeronautical Recommended Practice ARP-598 (Ref. 21). The three methods are very similar in the procedure and the reporting of results. In each method a sample of the specimen is filtered through a 0.45-micron cellulose membrane filter. The filter is examined under a microscope and the number of solid particles in a given area of the filter is counted. The particle counts are grouped in the following size ranges (in microns): 5 to 15, 15 to 25, 25 to 50, 50 to 100, over 100 (length-width ratio under 10:1), over 100 (length-width ratio over 10:1). The total number of particles present is calculated by statistical methods.

(2) Automatic Counting Methods:

The tedious nature of most particle-contaminant counting and weighing methods can be avoided through the use of automatic particle counters. Two types of automatic counters exist. Sample counters measure the number of particles in a sample of hydraulic fluid. On-stream counters record the number of contaminant particles in a system while it is in operation.

(a) Sample-type Automatic Counters:

One sample-type counter* is capable of counting solid particle contaminants and indicating their size. Electrodes on each side of a small channel detect a change in resistance whenever a contaminated sample of hydraulic fluid passes. The fluid sample must be

* Made by Coulter Electronics, Inc., Chicago.

TABLE 6-5.
EFFECTS OF VARIOUS CONTAMINANTS ON HYDRAULIC SYSTEM COMPONENTS¹⁸

	Scale	Rubber	Metal	Airborne Dust	Sand	Lapping Compound	Process Residues	Fibers
Oil	X			X	X			X
Reservoir	X	X	X	XX	X			X
Pump		X	XXX	X	X			X
Relief Valve		X	XX	X	X	X		X
Control Valves		X	X	X		X		X
Actuators		X	X	X				X
Accumulators	X	X	X	X			X	X
Pipe Fittings, Hoses, Etc.	X	X	X	XX			X	X
Filter	X	X	X	XX				X

X-Noticeable XX-Medium XXX-Strong

made conductive before testing by mixing it with a suitable solvent. Passing contaminants cause a voltage pulse in proportion to the size of the particle so that the number of particles within a certain size range can be determined. Measurement may be made down to about 5 microns.

Another sample-type counter* works on an electro-optical system capable of measuring and counting contaminant particles on test slides. Measurement may be made down to 1.0 micron. Also operating as an electro-optical device is a sample-type counter† which allows a sample of the fluid on a slide to oscillate past a photo-cell which counts and sizes the contaminant particles.

(b) *On-stream Automatic Counters:*

A second category of particle counters provides for automatic sampling of the hydraulic fluid. On-stream counters connect directly into an operating hydraulic system and tap fluid from a point in the flow believed to yield samples representative of the entire flow.

One commercially available on-stream device** counts and sizes particles in the 5-250 micron range. The counter automatically draws a fluid sample from a hydraulic system through a narrow passage fitted with a photoelectric detection system. The system makes contamination data available in terms of number of particles in various size ranges per unit volume of sample.

Another on-stream automatic counter design†† allows for the automatic sampling, sizing, and counting of particles greater in size than 10 microns. Measurements are accomplished by reflecting ultrasonic waves off contaminant particles.

6-2.4.2 Solid Particle Contamination Measurement by Weighing

Test Method: ASTM D-2387-65T (Ref. 22).

This method covers the determination of insoluble contamination in hydraulic fluids by gravimetric analyses. The contamination determined includes both particulate and gel-like matter, organic and inorganic, which is retained on a membrane filter disk of pore diameter as required by applicable specifications (usually 0.45 micron or 0.80 micron).

* The Cintel Flying-Spot Particle Resolver, made by Cinema Television Co., London.

† Casella Automatic Particle Counter and Sizer.

** HIAC Automatic Particle Counter.

†† A counter designed by Sperry Products Company for the Marshall Space Flight Center.

The insoluble contamination is determined by drawing a 100-ml sample of hydraulic fluid through a membrane filter disk and measuring the resultant increase in the weight of the filter. In addition, the filter disk is microscopically scanned for excessively large particles, fibers, or other unusual conditions.

Precision: Results should not be considered suspect unless they differ by more than the following amount:

- (a) Repeatability. 0.2 mg/100 ml
- (b) Reproducibility. 0.05 mg/100 ml

6-2.4.3 Solid Particle Contamination Measurement by Combined Counting and Weighing Methods

Many users of hydraulic fluids prefer to rely on more than one technique for determining contamination. The testing procedure required for MIL-H-5606B fluid is a good example. This particular fluid is considered below specification if it fails either a weight analysis or particle count test. According to weight, there must not be more than 0.3 mg of solid particle contaminants per 100 ml when the test is conducted under the provisions of Federal Test Method Standard No. 791a, Test Method 3009 (Ref. 19). According to the particle count, the number of contaminant particles must not exceed the values given in Table 6-6.

6-2.4.4 Liquid Contaminant Measurement

Determination of the amount of liquid contamination present in a hydraulic fluid can become a difficult problem, especially if the contaminant is soluble or miscible in the hydraulic fluid. Since most means of measuring liquid contaminants involve chemical reactions, it is usually a prerequisite to know what kind of contaminants are being measured so that the proper reagents may be used. However, the problem is somewhat simplified since the most common liquid contaminant is water. Procedures for determining other types of contaminants are usually specific to the chemical nature of the hydraulic fluid.

If the amount of water contaminant present in a hydraulic fluid is large, techniques such as dilution with a solvent which will separate the water into an immiscible layer can be used. When the amount of water present is small, two procedures are generally used. One depends upon the physical separation of water by means of an entraining nonsolvent and the other on a chemical reaction.

TABLE 6-6.
SOLID PARTICLE CONTAMINATION LIMITS IN HYDRAULIC
FLUID CORRESPONDING TO MIL-H-5606B

Particle Size Range, μ^*	Maximum Allowable Number of Solid Particles
5-15	2,500
16-25	1,000
26-50	250
51-100	50
Over 100	None

* μ = 1 micron = 10^{-4} cm

(1) *Test for Water in Petroleum and Other Bituminous Materials:*

Test Methods: Federal Test Method 3001.8 (Ref. 23)
ASTM D-95-62 (Ref. 24)

These methods are used to determine the water content of bituminous materials by distillation with a water immiscible, volatile solvent.

The sample is heated under reflux with a water-immiscible solvent which co-distills with the water in the sample. Condensed solvent and water are continuously separated in a trap, the water settling in the graduated section of the trap and the solvent returning to the still.

(2) *Test for Water With Karl Fischer Reagent:*

Test Methods: Federal Test Method 3253 (Ref. 25)
ASTM D-1744-64 (Ref. 26)

These methods cover the procedures for determining water in the concentration of 50 to 1,000 ppm in liquid petroleum products. The procedure, referred to as the Karl Fischer Method, or some variation of it, is widely used for the determination of moisture content of many materials. Although the test standards list the procedure for petroleum products only, it can be used on most materials where the reagents will not produce reactions that give false readings.

Sufficient Karl Fischer reagent is diluted with pyridine to adjust its strength to a water equivalence of 2 to 3 mg H_2O per ml of solution. Fifty ml of the sample is diluted with 50 ml of methanol-chloroform (1 part to 3 parts by volume). The sample is then added to the adjusted solution. If water is present, the solution will no longer be dry. A second adjustment with Karl Fischer reagent is made until the water equivalence of 2 to 3 mg H_2O per ml of solution is again reached. The amount of moisture present is then determined by the amount of reagent used to reach the second end point.

6-3 PRECAUTIONS

The exercise of certain precautions in the storage and handling of hydraulic fluids is vital for the safety of personnel and for the protection of the fluid. The introduction of contaminants into the hydraulic fluid and contact with incompatible materials are both to be avoided. Personal hazards from explosion, fire, skin poisoning, ingestive poisoning, and vapor inhalation are of even more concern. Anyone who stores and handles hydraulic fluids should know well the hazards they face and follow all recommended safety precautions.

6-3.1 HEALTH HAZARD

Skin poisoning, ingestive poisoning, and exposure to vapors and sprays of hydraulic fluids are common threats to hydraulic fluid handlers. Other dangers are due to the explosive or highly flammable nature of some liquids. Most hydraulic fluids, however, do not pose a serious health hazard. For specific information on the hazardous nature of a particular fluid, the fluid manufacturer should be consulted.

6-3.1.1 Precautions Against Poisoning

Skin poisoning or irritation caused by repeated handling of a hydraulic fluid, and ingestive poisoning caused by accidental swallowing are two hazards that can be easily guarded against. The swallowing of a hydraulic fluid is very rare. Nonetheless, poisonous hydraulic fluids should be clearly marked as such and an antidote or other first aid procedure should be known from the manufacturer's data or from cautionary

information on the fluid container. For all hydraulic fluids, the avoidance of extended contact with the skin is recommended. Although most hydraulic fluids, including synthetics, are not harmful to bare skin, prolonged contact should be avoided because many of the ingredients and additives may tend to dry out the skin. However, the effect is usually not long lasting if the exposure is not prolonged.

6-3.1.2 Precautions Against Dangerous Vapors and Sprays

Vapors and mists from many hydraulic fluids are generally irritating and cause coughing or sneezing. For these reasons prolonged inhalation of hydraulic fluid vapors or sprays is to be avoided. Even when the effects of short exposures are known to be nontoxic, indirect damage to the respiratory system could occur because of frequent or repeated irritations. Vapors from hydraulic fluids are most irritating when the fluid is at high temperatures, as the fluid may decompose and give off toxic vapors. Then, and at all times, the general rule is to avoid vapors from hydraulic fluids by working in well ventilated areas or by wearing protective masks.

6-3.2 DANGER OF EXPLOSION AND FIRE

The danger due to explosion of hydraulic fluids is possible during storage, handling, or use in a hydraulic system. The "explosive limits" of a substance are the lowest and highest concentrations of the vapors of the substance in the atmosphere which will form a flammable mixture (Ref. 27). Hydraulic fluids should not be stored where the temperature may become high enough to ignite the fluid. A common precaution that should be taken is to store the hydraulic fluid in an area removed from all possible sources of ignition and from areas where personnel or equipment would be endangered should the stored liquids be accidentally ignited.

Fire and explosion precautions are even more important in direct handling of hydraulic fluids. Pouring or draining of fluids near sources of ignition (such as direct flames or hot surfaces) is inviting disaster. Even fire-resistant fluids can ignite and continue to support flame if conditions are favorable (Ref. 28).

Serious fire hazards can occur when a liquid is in use in a hydraulic system. Because of the high pressure in components of the system, flammable hydraulic fluids in the event of a system failure (broken hose, line,

coupling)—can spray system components and surroundings that may be hot enough to cause ignition. If the liquid is conducting, the spray can also cause short circuits in electrical systems which, in turn, can cause ignition. Precautions against this sort of fire hazard are the responsibility of the system designer. If possible, the probable points of system failure should be situated so that, should a leak occur, the hydraulic spray will not be exposed to potential ignition sources.

6-3.3 OTHER PRECAUTIONS

Additional areas requiring precautions pertain to the relationship of hydraulic fluids with other materials.

All hydraulic fluids are incompatible with some materials. The designer takes this into account when choosing system components and a hydraulic fluid for the system. On occasion, however, users of a hydraulic system may desire to use a different hydraulic fluid. In changing to a different fluid, one should always investigate the safety of the change thoroughly. If the new fluid is incompatible with any system component, eventual system malfunction is probable. The fluid manufacturer can supply data on compatibility of his fluid with commonly used system materials.

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GLOSSARY

accumulator	A fluid pressure storage chamber in which fluid pressure energy may be stored and from which it may be withdrawn.		
bladder-type	A hydropneumatic accumulator in which the liquid and gas are separated by an expandable bladder or elastic bag.	boiling point	The temperature at which a fluid refluxes or distills under carefully specified conditions.
diaphragm-type	A hydropneumatic accumulator in which the liquid and gas are separated by a flexible diaphragm.	bulk modulus	The reciprocal of compressibility. It is usually expressed in pounds per square inch.
nonseparator-type	An accumulator in which a compressed gas operates directly upon the liquid in the pressure chamber.	bypass	An alternate route which provides passage for a liquid around a component.
piston-type	An accumulator in which a compressed gas operates on a piston which applies force to the stored liquid.	cavitation	A phenomenon of formation of cavities in a liquid across which the liquid can move with high velocity, producing a hammer effect on any object it strikes. It usually occurs where pressure is low and velocity high. Cavitation generally causes noise and damage to system components.
spring-loaded	An accumulator in which the compression energy is supplied by a spring.		
weight-loaded	An accumulator in which weights apply force to the stored liquid.	centipoise	A unit of absolute viscosity.
acid number	The quantity of base, expressed in milligrams of potassium hydroxide, that is required to neutralize the acidic constituents in one gram of sample.	centistoke	A unit of kinematic viscosity.
actuator	A device to convert fluid energy into mechanical motion.	cloud point	The temperature at which wax or other dissolved solids first precipitate during chilling under specified conditions.
additive	A chemical compound or compounds added to a liquid to change its properties.	coefficient of expansion	The change in weight per unit volume per 1° change of temperature.
autoignition temperature (AIT)	The temperature at which a liquid placed on a heated surface will ignite spontaneously.	compressibility	The reduction in volume of a liquid when pressure is applied. Compressibility is usually measured in terms of the bulk modulus, which is the reciprocal of compressibility.
base number	The amount of acid, expressed in terms of the equivalent number of	control	A device used to regulate the functions of a component or system to

	which it is usually connected; may be integral or remote.	plunger-type	A cylinder in which the movable element has the same cross-sectional area as the piston rod.
automatic	A control actuated in response to a signal from the system; also a control which actuates equipment in a predetermined manner.	single-acting	A cylinder in which the fluid pressure is applied in only one direction.
electric	A control actuated by an electrical device.	single-end rod	A cylinder with a rod extending from one end.
hydraulic	A control actuated by liquid pressure.	density	The mass of a material occupying unit volume at a specified temperature. Its dimensions are mass per unit volume.
liquid-level	A device which controls the liquid level, such as a float switch.	elastomer	An elastic, rubber-like material.
mechanical	A control actuated by linkages, cams, gears, screws, or other mechanical means.	emulsion	An intimate dispersion of one liquid within another.
pneumatic	A control actuated by air or other gas pressure.	film strength	The ability of a liquid to maintain a film.
pump	Controls applied to hydraulic pumps to adjust their output or direction of flow.	filter	A device through which a fluid is passed to separate material held in suspension. The filter medium is the material which removes the solids and consists of materials such as paper, cloth, finely woven screen, sintered metals, finely divided solids such as clay, activated charcoal, etc.
servo	A control actuated by a feed-back system which compares the output with the reference signal and makes corrections to reduce the difference.	bypass	A filter which receives only a portion of the total fluid flow. Continuous mixing of the filtered and unfiltered fluid ensures that it is all eventually filtered in a reasonable period of time.
conduction	Process by which heat flows from a region of higher temperature to a region of lower temperature within a medium or between different media in direct physical contact.	fire point	The temperature at which a liquid will burn continuously when ignited by a small flame under carefully specified conditions.
convection	Transference of heat by moving masses of matter.	fire-resistant fluid	A fluid difficult to ignite and which shows little tendency to propagate flame.
cylinder	A device for converting fluid energy into linear motion. It usually consists of a movable element such as a piston and piston rod, plunger or ram operating within a cylindrical bore.	flash point	The temperature at which a liquid gives off sufficient flammable vapors to ignite but not continue to burn when approached by a small flame under carefully specified conditions.
double-acting	A cylinder which moves in either direction due to fluid flow and pressure.	flow, laminar	A flow situation in which motion occurs as a movement of one layer of fluid upon another. This is synonymous with streamline flow.
double-end rod	A cylinder with a single piston and with a rod extending from each end.		
piston-type	A cylinder in which the movable element has a greater cross-sectional area than the piston rod.		

flow, steady state	A flow situation wherein conditions such as pressure, temperature, and velocity at every point in the fluid do not change.	synthetic	A material which, by definition, is nonpetroleum, but which may contain nonfunctional amounts of petroleum. Specifically, this permits petroleum to be used as a carrier for a constituent, i.e., for an additive, etc., but excludes petroleum used for any benefit of its properties <i>per se</i> .
flow, streamline	A flow situation in which motion occurs as a movement of one layer of fluid upon another. This is synonymous with laminar flow.		
flow, turbulent	A flow situation in which the liquid particles move in a random manner.	water-glycol-type	A fluid whose major constituents are water and one or more glycols or polyglycols and which may contain additional amounts of other constituents.
flow rate	The unit volume of a fluid flowing per unit of time.		
flow velocity	The rate of speed at which a volume of fluid passes a particular point in a passage.	water-oil emulsion type	A stabilized emulsion of water-oil, and which may contain additional amounts of other constituents. There are two types: (1) oil-in-water, a conventional soluble oil in which oil is dispersed in a continuous phase of water; and (2) water-in-oil, a dispersion of water in a continuous phase of oil.
fluid	A substance which yields to any pressure tending to alter its shape. Fluid, by strict definition, includes both liquid and gas.		
halogenated-type	A fluid composed of halogenated organic materials and which may contain additional amounts of other constituents.	fluid power	Power transmitted and controlled through use of a pressurized fluid.
hydraulic	A fluid suitable for use in hydraulic systems.	fluid power system	A system that transmits and controls power through use of a pressurized fluid within an enclosed circuit.
organic ester-type	A fluid composed of esters of carbon, hydrogen, and oxygen, and which may contain additional amounts of other constituents.	foam	An intimate mixture of gas and liquid occupying much more volume than the liquid alone.
petroleum-type	A fluid composed of petroleum hydrocarbons and which may contain additional amounts of other constituents.	freezing point	The temperature at which a fluid changes from liquid phase to solid phase.
phosphate ester-type	A fluid composed of phosphate esters and which may contain additional amounts of other constituents.	friction	Resistance to motion. Fluid friction is that friction due to the viscosity of the fluid.
polyalkylene glycol-type	A fluid composed of polyalkylene glycols or derivatives and which may contain additional amounts of other constituents.	heat exchanger	A device for transferring heat from a hot fluid to a cold one, without the two coming in contact with each other. When used as a fluid cooler in a hydraulic system, it may take the form of either a nest of pipes in a suitable container, through which coolant flows, or a radiator.
silicate ester-type	A fluid composed of organic silicates and which may contain additional amounts of other constituents.		
silicone-type	A fluid composed of silicones and which may contain additional amounts of other constituents.	hose	A flexible conduit for conveying fluid.

hydraulic power system	A means of energy transmission in which a relatively incompressible liquid (hydraulic fluid) is used as an energy-transmitting medium.		
hydropneumatic	The combination of hydraulic and pneumatic power in a unit.	oxidation	effectiveness of sealing increases with the pressure. A chemical reaction of oxygen with a liquid, resulting in the formation of oxidation products, which can cause changes in properties.
inhibitor	Any substance which slows, prevents, or modifies chemical reactions such as corrosion or oxidation.	packing	Any material or device used to prevent leakage. Packings, seals, and gaskets are often considered synonymous.
intensifier	A device which increases the working pressure over that delivered by a primary source. For example, such a device is one in which a low pressure acts on a large piston directly coupled to a smaller piston which then produces a higher pressure.	pilot line	A tube or hose which conducts control fluid.
isentropic	Having the same properties in all directions.	pipng	All pipe, tubing, hose, and fittings.
isothermal	Describing a condition of constant temperature.	piston ring	A sealing ring which normally fits in grooves in the piston head.
leaching	An operation in which the soluble component of a solid phase is dissolved and transferred to a liquid solvent.	poise	The standard unit of absolute viscosity in the centimeter-gram-second system. It is expressed in dyne seconds per square centimeter.
motor	A device for converting fluid energy into mechanical motion.	port	An opening at a surface of a component, e.g., the terminus of a passage. It may be internal or external.
fixed displacement	A rotary motor in which the displacement per revolution is fixed.	pour point	The lowest temperature at which a liquid will flow under specific conditions.
oscillatory	A rotary actuator giving an angular movement of less than 360°, sometimes referred to as a rotary hydraulic actuator.	pressure	Force per unit area. It is usually expressed in pounds per square inch.
rotary	A motor producing continuous rotary motion.	absolute	The sum of atmospheric and gage pressure.
variable displacement	A rotary motor in which the displacement per revolution is adjustable.	atmospheric	Pressure exerted by the atmosphere at any specific location. Sea level atmospheric pressure is approximately 14.7 psia.
neutralization number	A measure of the acidity or basicity of a liquid. It is defined as milligrams of potassium hydroxide required to neutralize the acidity in one gram of fluid or the equivalent of the basicity expressed in a similar manner.	operating	The pressure at which a system is operated.
O-ring	An endless packing ring of circular cross section normally mounted in a groove in such a manner that the	static	The pressure that exists if there is no motion in the liquid.
		suction	The pressure of the liquid at the inlet of a pump.
		pressure drop	The amount of pressure difference or the pressure required to force fluid through a component.
		pressure loss	The fall in pressure due to hydraulic friction in a component or circuit.

	Pressure losses at full flow are often appreciable; there is, however, none when flow ceases.			body at a lower temperature when the bodies are separated in space, even when a vacuum exists between them.
pump	A device which converts mechanical energy into fluid energy.	reservoir		A container for fluid from which the fluid is withdrawn and returned after circulation through the system. The reservoir may be open to the atmosphere, or it may be closed and pressurized.
axial piston constant volume	A pump with a fixed volumetric output and with multiple pistons having their axis parallel to the drive shaft.			
axial piston variable volume	An axial piston pump with an adjustable controlled volumetric output.	Reynolds number		A dimensionless number used in considerations of fluid flow and given by the formula: $R_n = (\text{Velocity}) (\text{pipe diameter}) / \text{Kinematic viscosity}$. When the Reynolds number is below 2,000, laminar flow generally exists; at higher values, flow may be either laminar or turbulent, but the higher the value the less likely the flow will be laminar.
centrifugal	A pump having an impeller rotating in a housing with liquid carried around the periphery of the housing and discharged by means of centrifugal force.			
gear	A pump having two or more intermeshing gears or lobed members enclosed in a suitably shaped housing.	seal		A material or device designed to prevent leakage between parts, moving or static.
radial piston constant volume	A pump with a fixed volumetric output having multiple pistons disposed radially.	servomechanism		Any mechanism which uses power magnification and in which there is incorporated a means of relating the speed and travel of the input and output.
radial piston variable volume	A radial piston pump with an adjustable volumetric output.			
reciprocating	A pump having reciprocating pistons to pressurize fluid.	solenoid		An electromagnet consisting of a wire-wound coil with a moving plunger which moves when the electric current is switched on.
screw	A pump having one or more screws rotating in a housing.	specific gravity		The ratio of the weight of a given volume of fluid to the weight of an equal volume of water.
two-stage	A pump with two separate pumping elements connected in a series. The primary stage may be used to ensure that the second main stage is not starved for fluid, or it may produce much of the pressure rise through the pump.	specific heat		The heat required to raise a unit weight one degree of temperature.
vane, constant volume	A pump having a fixed volumetric output with multiple vanes within a supporting rotor, encased in a cam ring.	stability		Resistance to permanent changes in properties under normal storage and use conditions.
vane, variable volume	A vane pump having suitable means of changing the volumetric output.	hydrolytic		Resistance to permanent change in properties caused by chemical reaction with water.
pump slippage	Internal leakage in a pump from outlet to inlet side.	oxidation		Resistance to permanent changes in properties caused by chemical reaction with oxygen.
radiation	The process by which heat flows from a high-temperature body to a	thermal		Resistance to permanent changes in properties caused solely by heat.

stoke	The standard unit of kinematic viscosity in the centimeter-gram-second system. It is expressed in square centimeters per second.	gate	A valve with a gate which is raised or lowered by the action of a screw or other means to close or open the flow passage.
strainer	A filter made from wire mesh and capable of removing the larger particles of solids from a fluid.	globe	A valve with a plug, ball, or disc, which by action of a screw or other means, is pulled away from or lowered into a corresponding seat to open or close the flow passage.
switch, pressure	A switch operated by pressure and used for (a) controlling pressure between predetermined limits, (b) starting or stopping a sequence when a certain pressure is reached, and (c) as a safety device.	needle	A valve with a tapered needle which is pulled away from or forced into a corresponding seat. The tapered needle permits gradual opening or closing of the passage.
thermostat	A device for controlling temperature either by switching on and off an electric current or by opening and closing a valve in a liquid line.	open center	A valve which in the center position connects all ports.
torque	Force applied through a rotary path of motion.	pilot	A valve applied to operate another valve or control.
vacuum	A pressure which is less than the prevailing atmospheric pressure.	pilot-operated	A valve in which operating parts are actuated by pilot fluid.
valve	A device for controlling flow rate, direction of flow, or pressure of a liquid.	poppet-type	A valve construction which closes off flow by a poppet seating against a suitable seating material. Normally considered a dead-tight seal. The poppet may be a ball, a cone, or a flat disk.
cam-operated	A valve in which the spool is positioned mechanically by a cam.	pressure reducing	A valve which maintains a reduced pressure at its outlet regardless of the higher inlet pressure.
check	A valve which permits flow of fluid in one direction only and self closes to prevent any flow in the opposite direction.	relief	A valve which opens when a set pressure is reached to prevent further rise of pressure in a system or to keep the pressure constant. The relief valve limits pressure which can be applied to that portion of the circuit to which it is attached.
closed center	A valve which in the center position has all ports closed.	sequence	A valve which directs flow to a secondary portion of a fluid circuit in sequence. Flow is directed only to that part of the circuit which is connected to the primary or inlet port of the valve until the pressure setting of the valve is reached. At this time, the valve opens and pressure in the secondary port may vary from zero to near the setting of the primary side with no variation in the primary pressure.
directional	A valve whose primary function is to direct or prevent flow through selected passages.	shuttle	A connective valve which selects one of two or more circuits because
flow control	A valve whose primary function is to control flow rate.		
flow dividing	A valve which divides the flow from a single source into two or more branches.		
flow dividing, pressure compensating type	A valve which divides the flow from a single source into two or more branches at constant ratio, regardless of the difference in the resistances of the branches.		
four-way	A valve having four controlled working passages, usually ending in four external ports.		

	flow or pressure changes between the circuits.			minimum. As the velocity increases at the Venturi throat, the pressure decreases appreciably. Venturi tubes are often used as flow meters, the difference of pressure between the entrance to the Venturi and the throat varying as the square of flow.
solenoid-operated	A valve which is operated by one or more solenoids.			
spool-type	A valve construction using a spool consisting of undercuts or recesses on a cylinder of metal. The spool is fitted in a bore containing annular undercuts. Movement of the spool in the bore connects ports uncovered by the spool undercuts.	viscometer		A device for measuring viscosity.
		viscosity		A measure of the internal friction or the resistance of a fluid to flow.
three-position	A valve having three positions to give three selections of flow conditions.	absolute		The force required to move a plane surface over another plane surface at the rate of one centimeter per second when the surfaces are one centimeter square and are separated by a layer of fluid one centimeter in thickness. This force is known as the poise.
three-way	A directional control valve having three distinctive external working connections.			
two-position	A valve having two positions to give two selections of flow conditions.			
two-way	A directional control valve having two distinctive external working connections.	kinematic		The ratio of absolute viscosity to the density of a fluid. The unit of kinematic viscosity is the stoke. Viscosity in stokes, multiplied by density at the test temperature equals the absolute viscosity in poise.
unloading	A valve which allows pressure to build up to an adjustable setting, then bypasses the flow as long as the preset pressure is maintained on the pilot port by a remote source. Its primary function is to unload a pump.	Saybolt Universal Seconds (SUS)		Saybolt Universal Second viscosity is the time in seconds required for 60 cc of liquid to flow through a standard orifice at a given temperature.
time delay	A valve in which the change of flow occurs only after a desired time interval has elapsed.	Viscosity Index (V.I.)		A measure of the viscosity-temperature characteristics of a fluid as referred to that of other fluids.
vapor pressure	The pressure exerted by a material under consideration at a specified temperature.	volatility		The property of a fluid describing the degree to which it will vaporize under given conditions of temperature and pressure.
venturi	A local contraction in a pipe which is shaped so that the loss of pressure due to friction is reduced to a			

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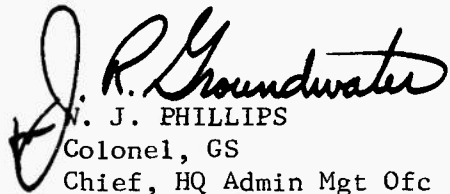
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